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EVALUATION OF LAMINAR FLOW CONTROL SYSTEMS CONCEPTS FOR SUBSONIC COMMERCIAL TRANSPORT AIRCRAFT

EXECUTIVE SUMMARY

W. E. Pearce

McDonnell Douglas Corporation
Douglas Aircraft Company
Long Beach, California 90846

CONTRACT NAS1-14632
DECEMBER 1982

National Aeronautics and
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Langley Research Center
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FOREWORD

This document summarizes the contract work performed by Douglas Aircraft Company, McDonnell Douglas Corporation, on laminar flow control (LFC) under NASA Contract NAS1-14632 entitled Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft. The contract activity is part of the overall Aircraft Energy Efficient (ACEE) program supported by NASA through its Langley Research Center.

Acknowledgments for their support and guidance are given to the NASA LFC Project Manager, Dr. R. Muraca; to the Project Technical Monitors, Mr. R. Wagner and Mr. J. Cheely, and to the Project Chief Scientist, Mr. A. Braslow; also to Dr. W. Pfenninger and to the NASA on-site representative at Long Beach, Mr. J. Tulinius.

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W. Nelson	Structures
J. Hughes	Wind tunnel testing

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1. SUMMARY

This study, Evaluation of Laminar Flow Control Systems Concepts for Subsonic Commercial Transport Aircraft, considered all aspects of the application of laminar flow control (LFC) to commercial transport aircraft in operation. All problems were identified and tackled systematically until resolved. Program activities included configuration design and analysis, performance and economic analysis, fabrication development, environmental studies, contamination avoidance systems design and testing, structural design/analysis and testing, and wind tunnel testing. This report summarizes the results achieved as of December 1980. The full report on the work accomplished is presented in the material of Reference 1.

LFC was achieved by controlling suction through the external surface of the wing to stabilize the laminar boundary layer and prevent transition to turbulent flow, thus achieving significant drag reduction.

An objective of the program was to take advantage of any new and advanced technology consistent with a mid-1990s aircraft time frame. With this in mind, it was decided to examine the possibilities of using porous materials at the surface to control suction airflow rather than a series of very fine slots as used previously in the Northrop X-21 aircraft program. Due to the very limited data base available on the use of porous materials for achieving LFC, an extensive survey of possible porous materials and their application was undertaken. This involved design studies, fabrication development, and structural and aerodynamic testing.

The most promising LFC surfaces were first tested in the Douglas wind tunnel at Long Beach to determine airflow characteristics and LFC performance. (The 2.14-m [7-ft] chord swept-wing LFC wind tunnel model was funded by Douglas in support of the LFC program.) As a result, two primary suction surfaces were selected, a smooth finely woven stainless steel mesh manufactured under the name Dynapore and an electron beam (EB) perforated titanium sheet material fabricated using Steigerwald equipment. LFC glove panels were then fabricated and tested for structural suitability. The EB-perforated titanium LFC surface was finally selected because of its superior structural and damage-resistance properties.

Preliminary design studies resulted in an initial LFC airplane configuration that was updated at intervals and used as a baseline for LFC system and structural design and for configuration trade studies.

The most significant trade study considered LFC on both upper and lower wing surfaces versus LFC on the upper surface only. It was found that with LFC suction to either 70-percent chord on both surfaces or to 85-percent chord on the upper surface only, the reduction in drag coefficient and the total suction airflow required were of the same order. The advantages of having suction on the upper surface only — simplicity, reduced damage vulnerability, and the availability of access through the lower surfaces for maintenance — are obvious. Not so obvious perhaps is the main advantage, the possibility of using a shield at the leading edge to avoid surface contamination. The shield also

functions as a high-lift device and is retracted into the lower surface after use. This trade study showed the superior performance of the upper-surface-suction-only configuration. It was therefore selected for the baseline LFC aircraft to be used in subsequent studies.

The LFC aircraft was also compared with an advanced turbulent aircraft configuration designed for the same mission. This trade study clearly showed the advantages of LFC with respect to lower operating costs and reduced fuel consumption, which became more significant with increased fuel prices.

In examining all aspects of the practical application of LFC to commercial transport aircraft, no problem was found for which a practical solution could not be identified, as shown by analysis, design studies, and development testing undertaken in this program. The overall results indicate that the LFC aircraft configuration, suggested by Douglas in this study, could be developed into a practical design that would result in significant fuel savings and operating cost benefits.

2. INTRODUCTION

This investigation into the possibilities of using laminar flow control (LFC) on commercial transport aircraft was initiated by NASA in response to the growing need for energy conservation.

Fuel savings result directly from the drag reduction that can be achieved by using LFC. The successful application of LFC to commercial airplane operation would result in a major reduction of fuel consumed by airline fleets throughout the world. With rising fuel costs, increasing economic benefits are also obtainable.

The airflow over the surface of an airplane is initially laminar within the boundary layer, but this low-drag condition is unstable and transition to turbulent flow normally occurs in a very short distance. On a swept wing, this instability is aggravated by cross-flow conditions in regions of steep pressure gradients. Transition can also occur due to the spanwise flow along the attachment line at the leading edge. In all of these cases, transition to turbulent flow can be avoided by the use of suction through the surface to stabilize the laminar boundary layer.

Ideally the suction airflow would be distributed over the whole area using a porous surface, but when this study was undertaken a practical solution to achieving this did not exist. Very fine suction slots had been used previously to create intermittent suction at frequent intervals in order to sustain laminar flow. Although slotted systems have been tested successfully, full-scale flight testing of a slotted system on the Northrop X-21 airplane wing in the early 1960s demonstrated many of the difficulties of making such a system reliable, and it was not considered to be commercially practical at that time. The approach adopted by Douglas was therefore directed toward taking full advantage of recent advances in technology to achieve a practical, reliable, and economical LFC system for commercial transport aircraft by using suction distributed through porous surfaces (see Reference 2).

3. SYMBOLS AND ABBREVIATIONS

AR	=	aspect ratio
b	=	wing span
c	=	wing chord
C_d	=	drag coefficient
C	=	airfoil lift coefficient — unswept
C_L	=	wing lift coefficient
$C_{L_{max}}$	=	maximum wing lift coefficient
C_P	=	pressure coefficient
C_Q	=	suction flow coefficient
C_W	=	local wing chord
℄	=	center line
DOC	=	direct operating cost
dB	=	sound level in decibels
E	=	Young's modulus of elasticity
E^3	=	energy efficient engine — initiated under NASA ACEE program
EB	=	electron beam
f	=	friction loss
FT (ft)	=	feet
I	=	moment of inertia
K	=	ballistic coefficient
LB	=	pound
L/D	=	lift/drag ratio
LFC	=	laminar flow control
M	=	Mach number
M_∞	=	streamwise Mach number
M	=	airfoil Mach number — unswept
M_{cruise}	=	cruise Mach number
OASPL (SPL)	=	overall sound pressure level

OEW	=	operator's empty weight
PGME	=	propylene glycol methyl ether
PLM	=	plastic laminating mold
PSF	=	pounds per square foot
PSI	=	pounds per square inch
q	=	airflow dynamic pressure
R	=	fatigue stress ratio
R_c	=	chord Reynolds number
SLS	=	sea level static
SPFDB	=	superplastic-formed/diffusion-bonded
SRLT	=	silicone rubber laminating tool
T/C (t/c)	=	thickness/chord ratio
TI (ti)	=	titanium
TOGW	=	takeoff gross weight
U+L	=	suction on upper and lower surfaces
USO	=	suction on upper surface only
$V_{approach}$	=	aircraft landing approach speed
V_W	=	average local velocity through suction surface
V_∞	=	freestream velocity
WT	=	weight
X_W	=	spanwise distance from wing ℄
X_{TR}	=	distance to boundary layer transition
α	=	angle of attack
Λ	=	sweepback angle

4. LFC SURFACE DEVELOPMENT

INITIAL SURVEY

Selection of a satisfactory LFC suction surface was the first study objective. Removal of a small fraction of the boundary layer at the surface can be used to stabilize a laminar boundary layer and prevent transition to high-drag turbulent flow. This method can be used effectively with several forms of laminar boundary layer instability that can occur on a swept wing, including those due to Tollmien-Schlichting waves, adverse pressure gradients, cross flow, and spanwise flow along the attachment line.

Preceding LFC investigations have concentrated mainly on the use of multiple suction slots in the surface and have provided an extensive data base for this approach. For this investigation at Douglas, however, it was decided to also pursue the alternative possibility of using porous or perforated surfaces and to take full advantage of any useful recent developments in technology, although this would require additional development work.

Following an initial survey of possible suction surfaces and supporting structural arrangement, some of which are illustrated in Figure 4-1, a number of surfaces were selected and tested in the Douglas wind tunnel at Long Beach, California. The test panels were inserted in a flat plate model as shown in Figure 4-2. As an initial screening process, the extent of laminar flow achieved beyond the test surface was measured as influenced by the level of suction through the surface. The results were compared with those using a smooth nonporous surface at Reynolds numbers up to 11×10^6. Some typical early results are shown in Figure 4-3. As a result, the most promising suction

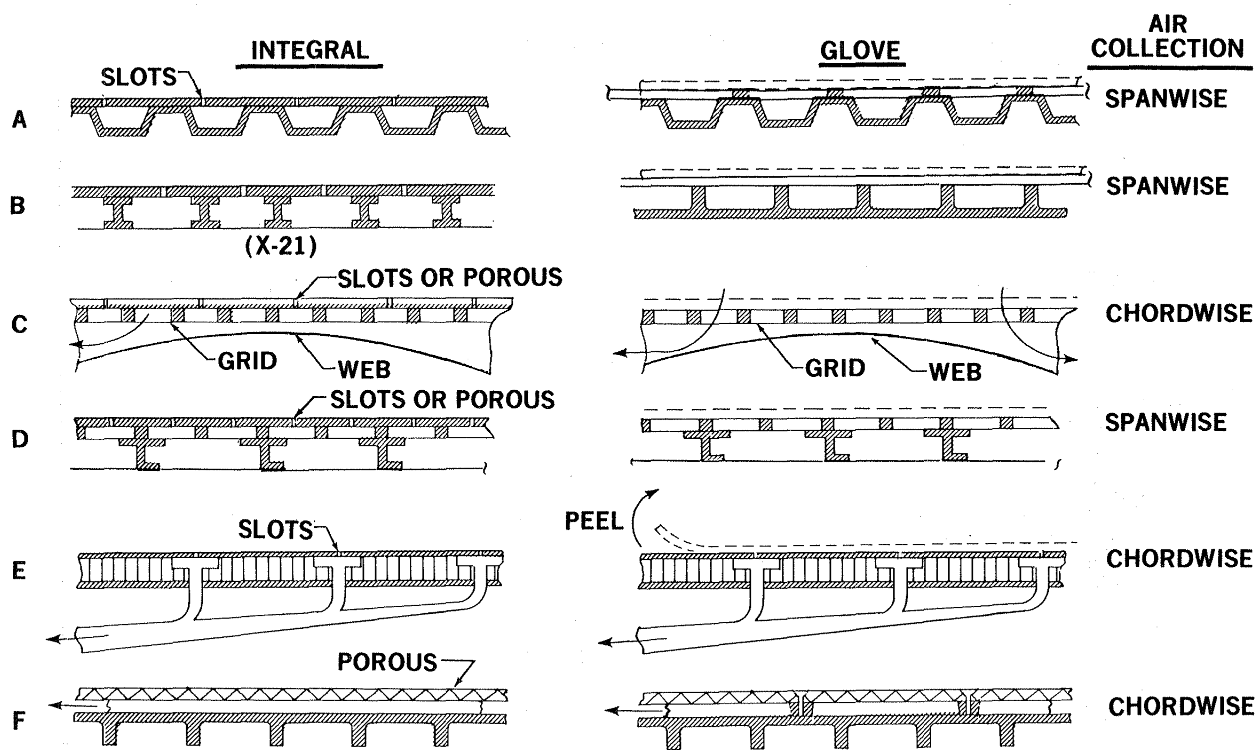


FIGURE 4-1. LFC SURFACE DESIGN CONCEPTS

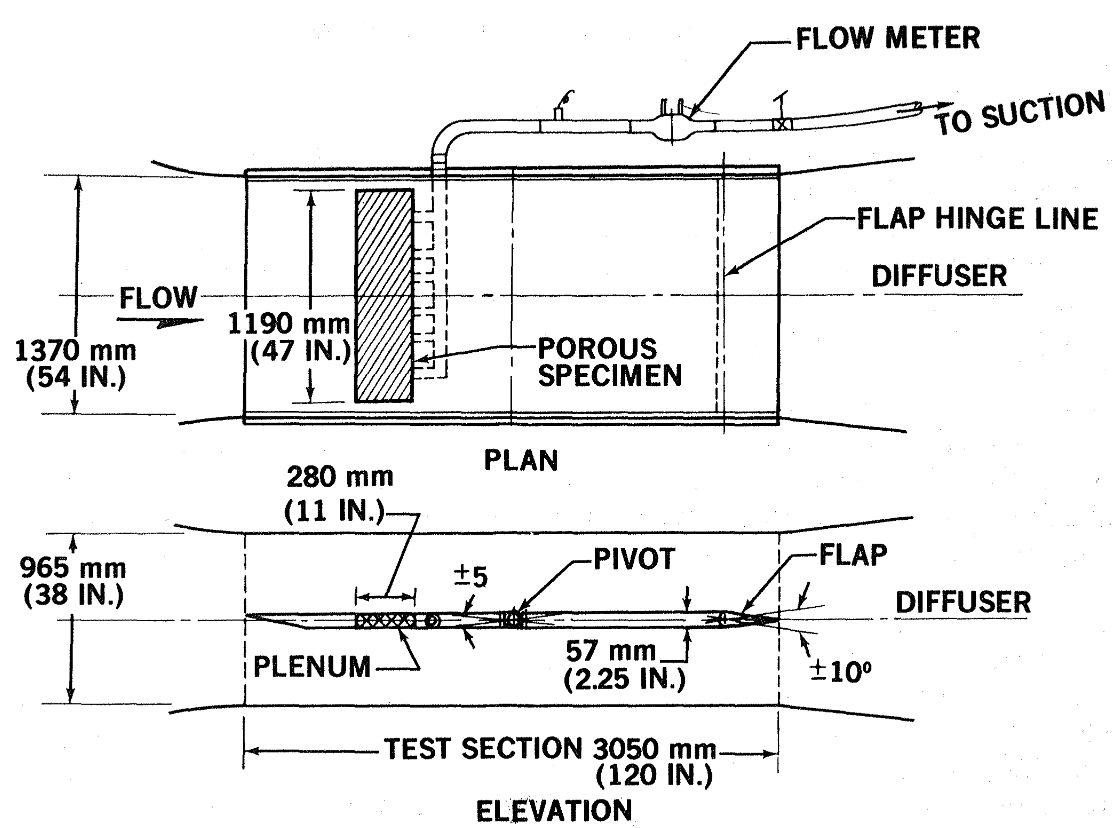


FIGURE 4-2. WIND TUNNEL MODEL TEST FOR LFC SURFACES

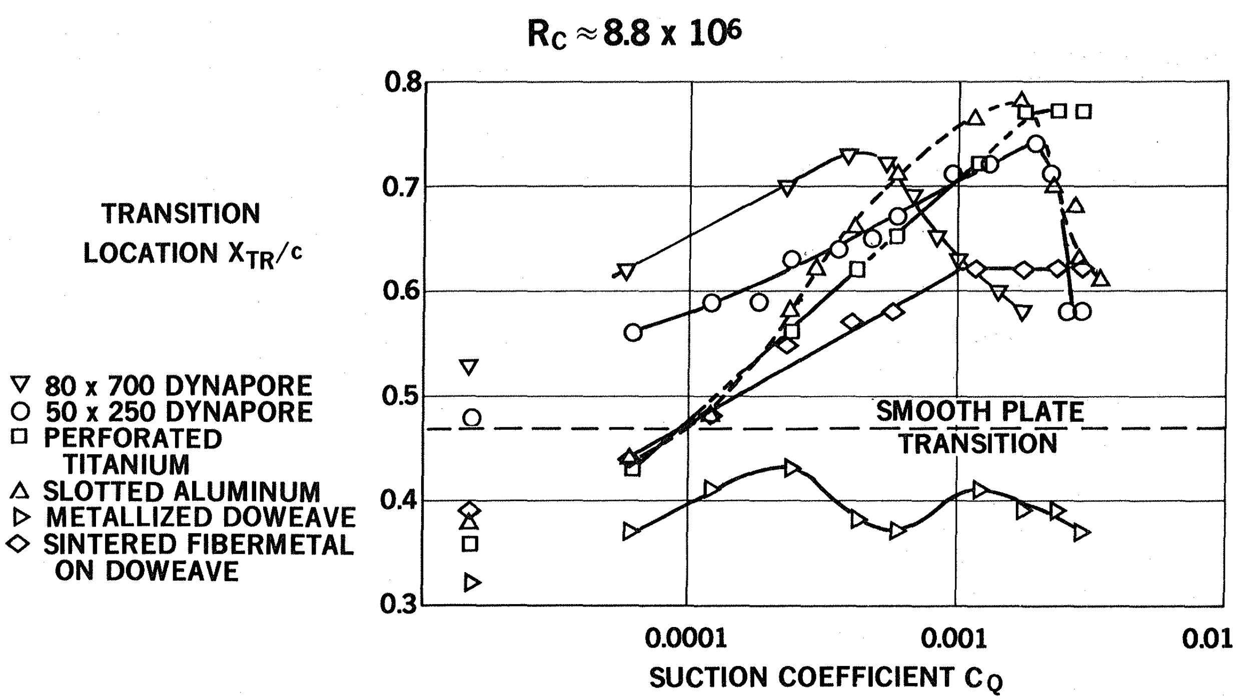


FIGURE 4-3. COMPARATIVE EFFECTIVENESS OF LFC SURFACES

surfaces were selected for further consideration. These were porous Dynapore, electron beam (EB) perforated titanium, and strip porosity variations of the two, all of which performed satisfactorily during the preliminary wind tunnel testing.

LFC SURFACE SELECTION

Slotted Surface

Experience with slotted surfaces has indicated a number of practical problems, including the following:

- The slots need to be as narrow as 0.076 mm (0.003 in.) and are difficult to machine satisfactorily in the tough, corrosion-resistant surface needed.
- Slot-width tolerances would need to be extremely tight in order to avoid significant suction variations along the span.
- Because the slots are normally cut after the surface is attached to its supporting structure, the release of any locked-up stresses during fabrication could cause variations in slot width and contour.
- On tapered wings, the slots, which should follow the isobars to avoid spanwise pressure gradients, tend to be too close at the wing tip unless the number of slots is reduced. Ending a slot along the span could result in transition occurring at that point.
- Should damage occur during fabrication or in service, the repair — and alignment of slots in a repair patch with those already existing — would be very difficult.

Because of these known problems, the porous or perforated surfaces were given primary consideration.

Porous Surface

Dynapore was the most satisfactory porous material tested. It is the trade name for a material woven from fine stainless steel wire. The material is then calendered between rollers under pressure to produce a smooth, flat surface that performed very well as an LFC surface during wind tunnel testing. The porosity can be controlled by varying the wire diameter, the weave, and the calendering pressure. To provide increased strength and stiffness the fine outer surface of 80 by 700 mesh was diffusion-bonded to a coarser 80 by 80 sublayer. The effectiveness of the diffusion bonding is illustrated in the greatly enlarged photographs presented in Figure 4-4.

The Dynapore surface was supported by a panel fabricated by using Douglas-patented Lockcore construction, as illustrated in Figure 4-5. The outer laminate and the bond are porous to allow suction air to flow into integral ducting formed by the corrugations. The construction was further modified by the addition of a perforated fiberglass sublayer, as shown in Figure 4-6, to reduce surface porosity and increase surface strength.

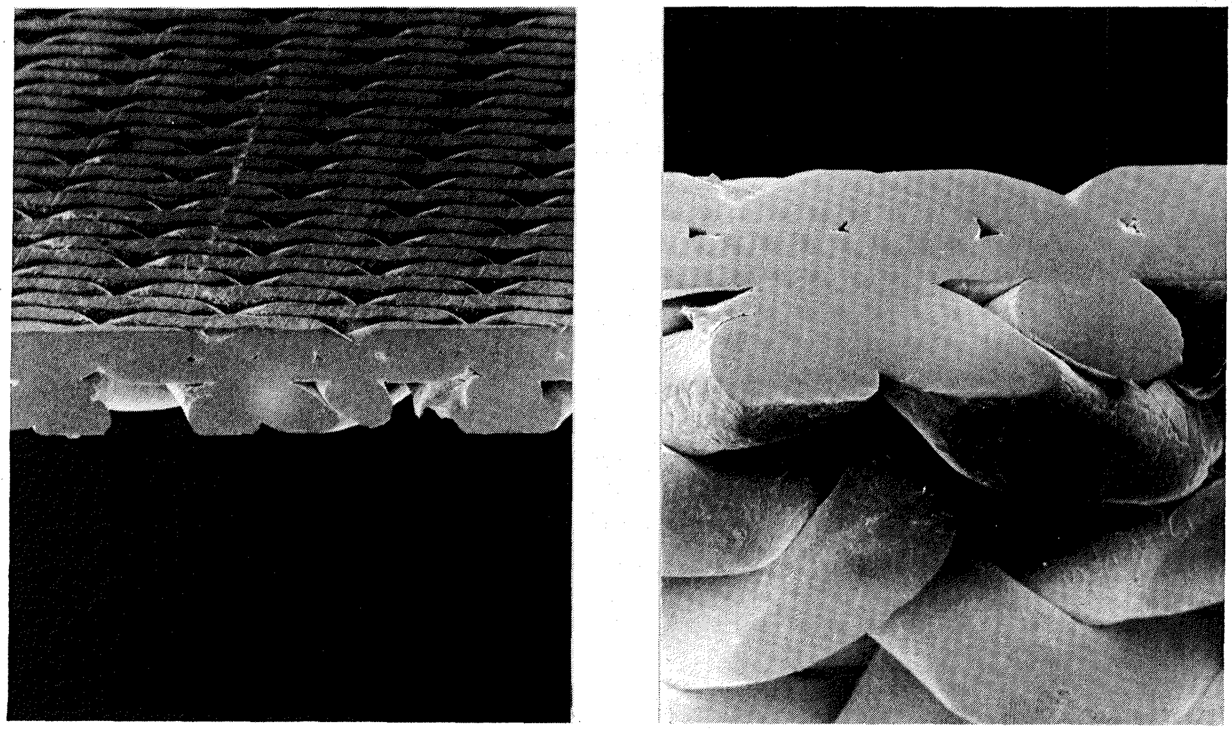


FIGURE 4-4. 80 BY 700 DYNAPORE SURFACE PLUS DIFFUSION-BONDED 80 BY 80 SUBLAYER

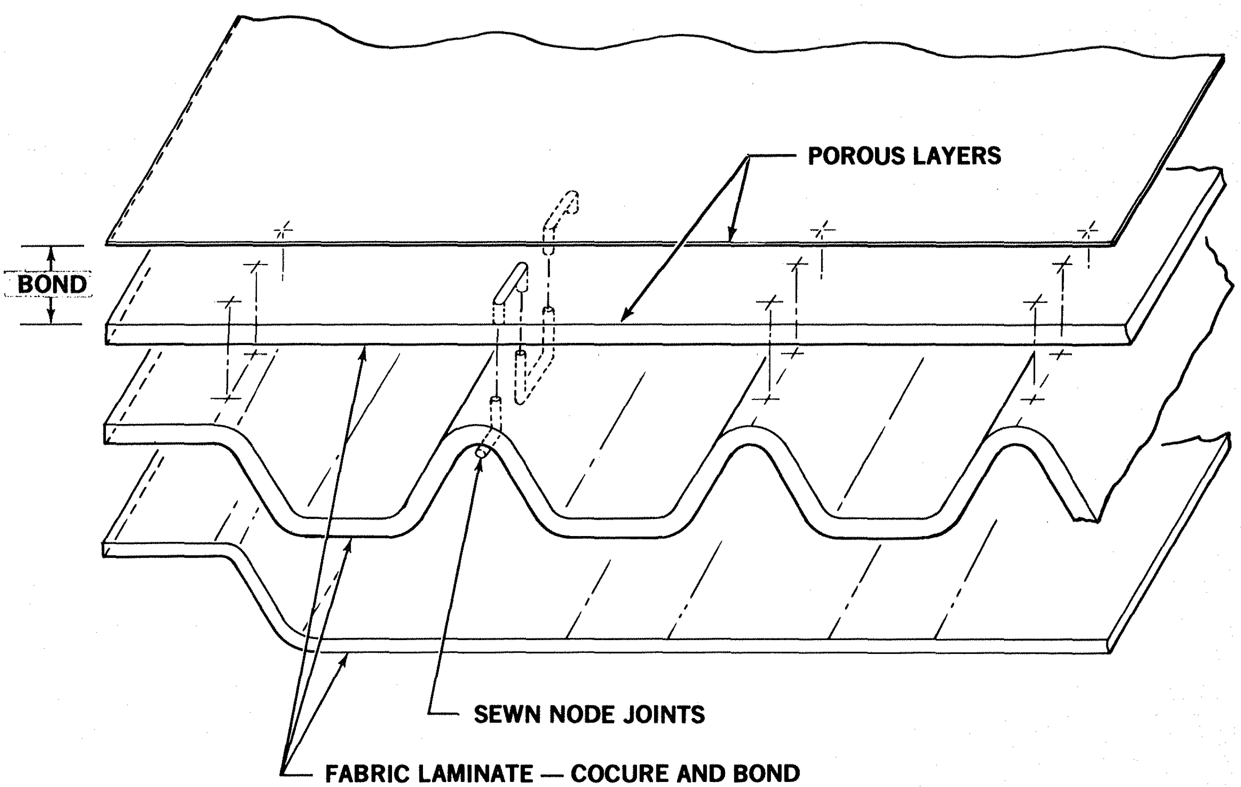


FIGURE 4-5. TYPICAL LOCKCORE PANEL CONSTRUCTION

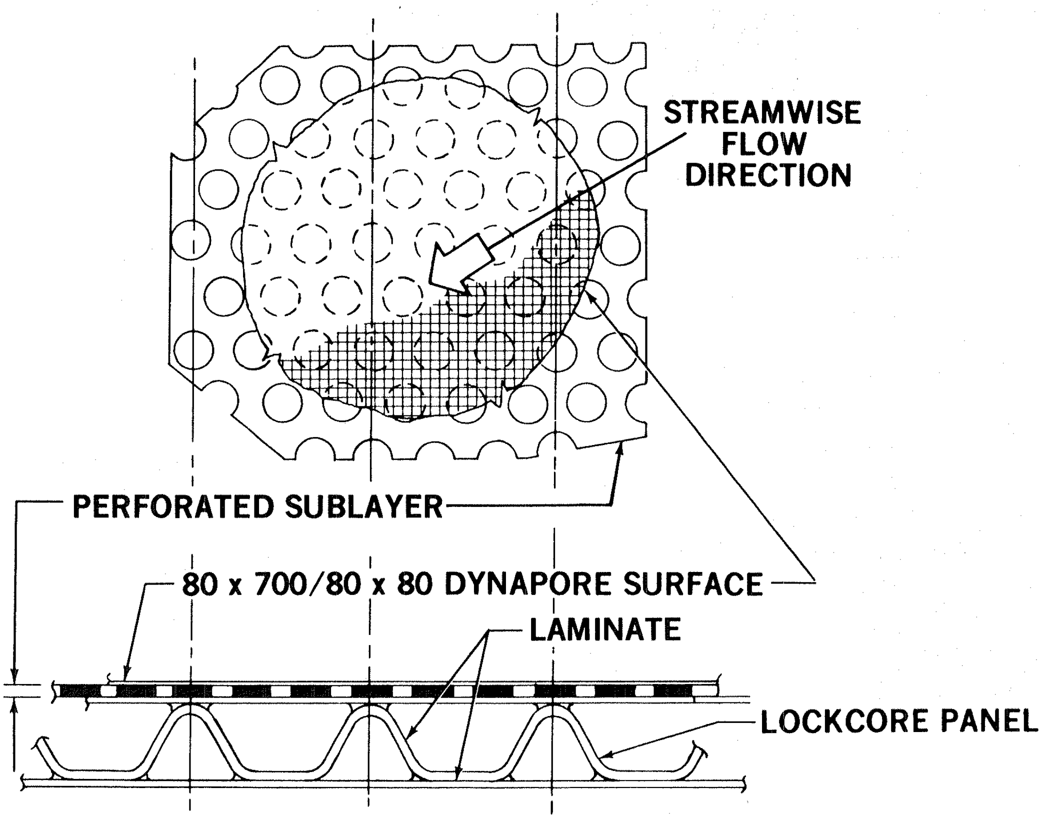


FIGURE 4-6. GLOVE PANEL WITH PERFORATED FIBERGLASS SUBLAYER

Subsequent wind tunnel testing showed that the resulting "polka dot" porosity was satisfactory for LFC. The final development with this construction was to replace the perforated glass laminate with a more finely perforated stainless steel sheet diffusion-bonded to the Dynapore layers to further increase strength and resistance to impact.

Perforated Surface

Previous attempts at achieving LFC using a perforated surface were not satisfactory because the smallest holes that could be produced economically were too large for satisfactory LFC performance. Making use of technology development, Douglas was able to use the perforated surface shown in Figure 4-7. The 0.63-mm (0.025-in.) thick 6AL4V titanium alloy sheet was drilled by Pratt & Whitney Aircraft to provide the fine perforations required, using EB-perforating equipment produced by Steigerwald Strahltechnic GMBH in Germany. The holes are only 0.063 mm (0.0025 in.) diameter at the outer surface. The taper is a natural outcome of the electron beam drilling process and ensures that any particles entering at the outer surface will not jam and clog the porosity. The minimum reliable hole diameter possible using existing EB drilling equipment is approximately one-tenth of the sheet thickness. On this basis, the holes used are of the minimum diameter possible for the thickness of material which is also considered to be a minimum for adequate resistance to impact from rain, hail, and accidental

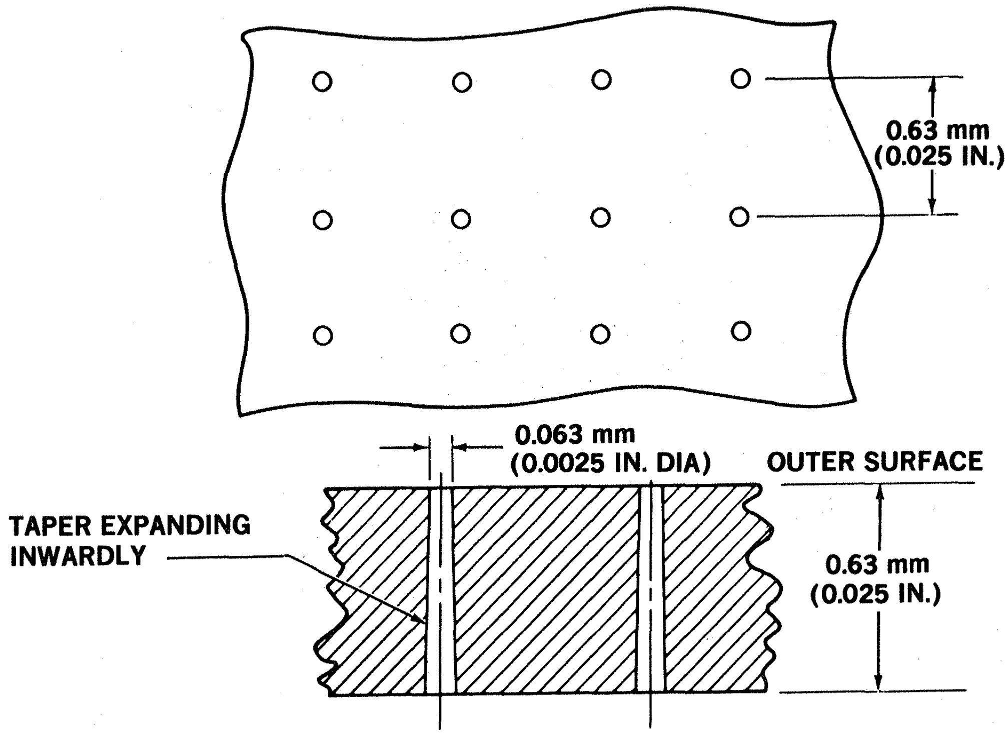


FIGURE 4-7. SUCTION SURFACE, ELECTRON-BEAM-PERFORATED TITANIUM

damage. The Steigerwald chart of Figure 4-8 confirms that the selected configuration is pushing the state of the art with respect to hole size and material thickness. It also shows that the holes can be produced at the extremely rapid rate of 850 per second. The maximum rate varies with the hole size, sheet thickness, and material. The holes are remarkably accurate and of true circular shape at the outer surface, as shown in Figure 4-9. Their small diameter, which is less than that of a human hair, is illustrated by their comparison with a paper clip in Figure 4-10.

The EB-perforated surface was bonded directly to a corrugated fiberglass substructure to form a simple LFC glove panel, as shown in Figure 4-11.

Surface Structural Testing

Honeycomb sandwich beams of the type shown in Figure 4-12 were used to determine tensile, compression, and fatigue characteristics of the surface materials. The requirements are that the surface should be able to strain with the primary structure to its working stress level without damage, and should have an adequate fatigue life. The allowable strain levels at limit load and ultimate load assumed for an advanced carbon-fiber/epoxy primary structure were ±0.0027 and ±0.004 respectively. Currently, the allowable ultimate strain level for a carbon-fiber/epoxy laminate is limited at Douglas to ±0.003.

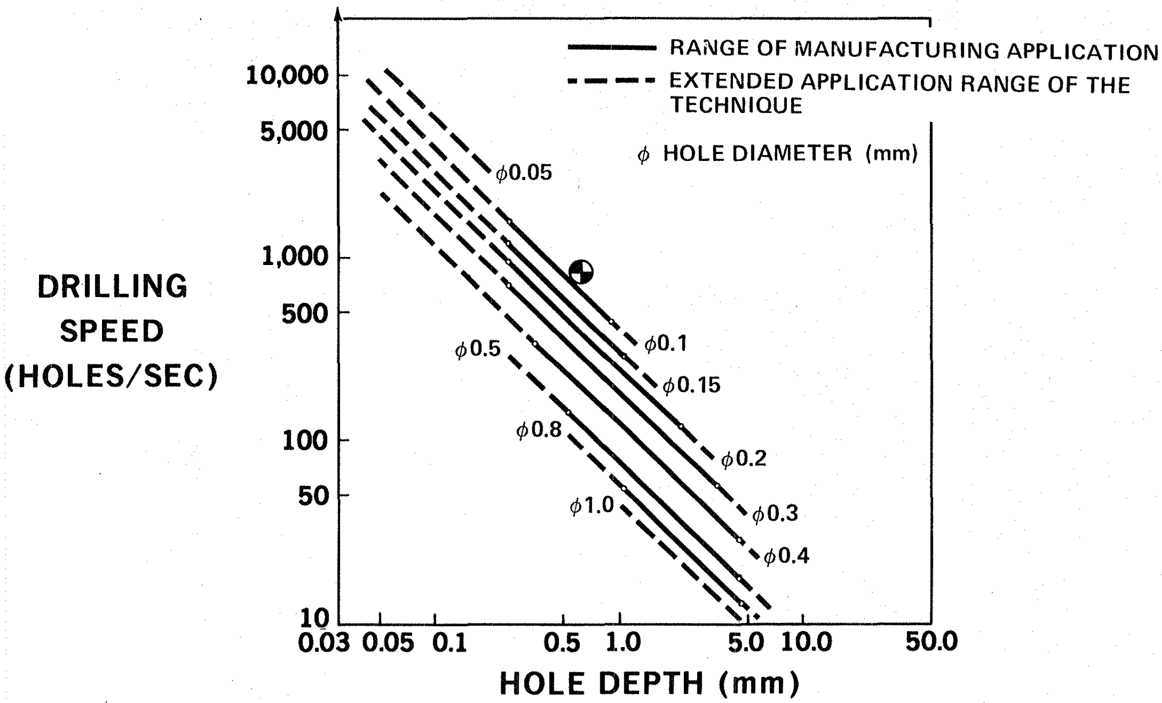


FIGURE 4-8. ELECTRON BEAM DRILLING SPEEDS

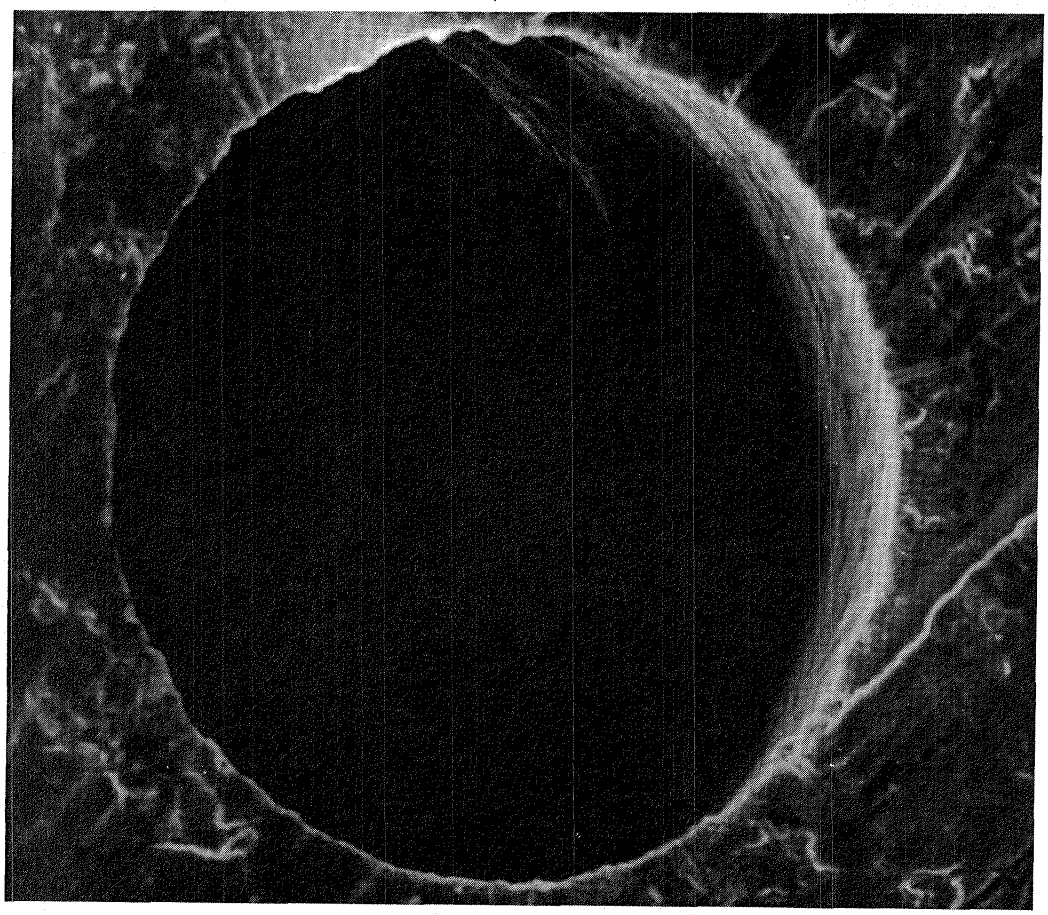


FIGURE 4-9. ELECTRON-BEAM-DRILLED HOLE

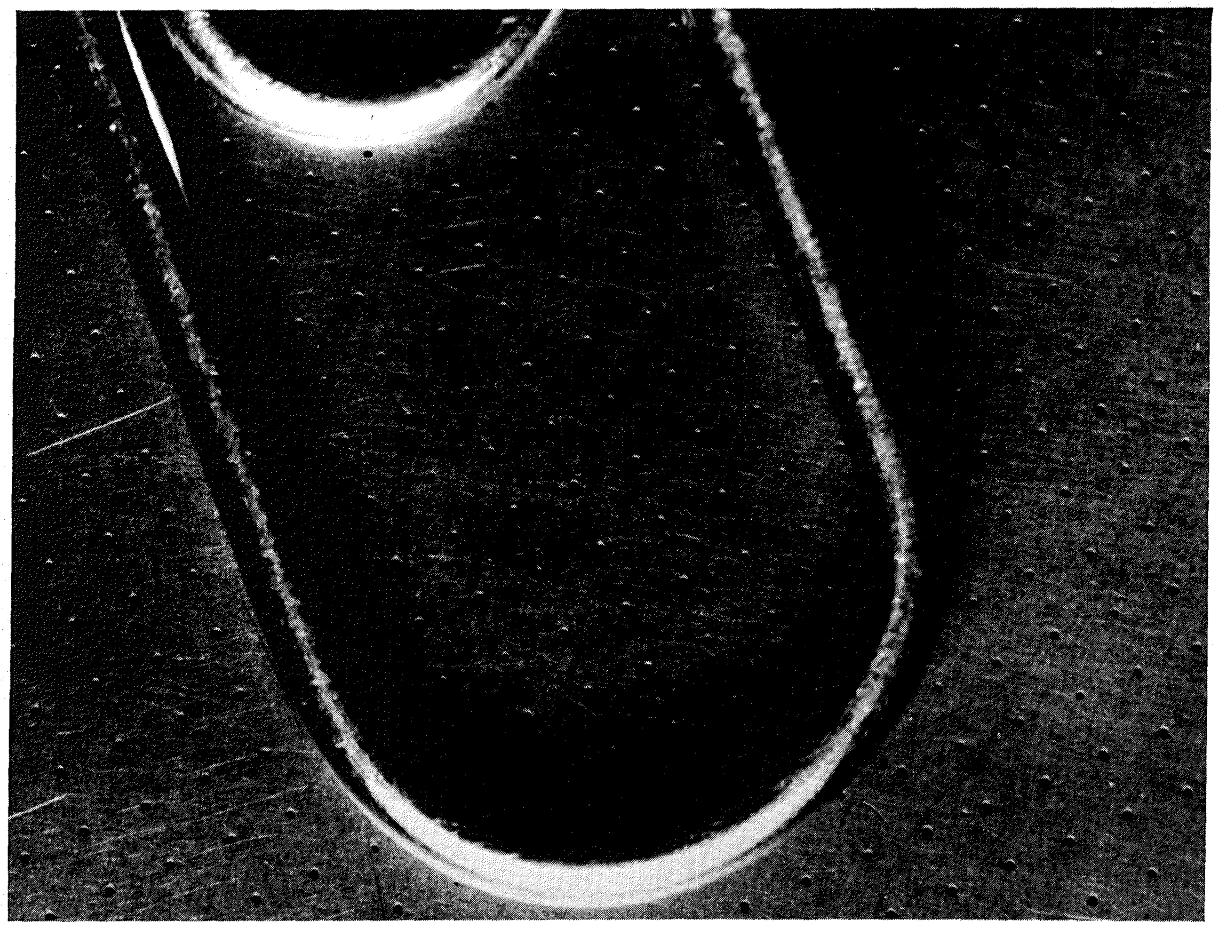


FIGURE 4-10. ELECTRON BEAM PERFORATIONS COMPARED WITH ORDINARY PAPER CLIP

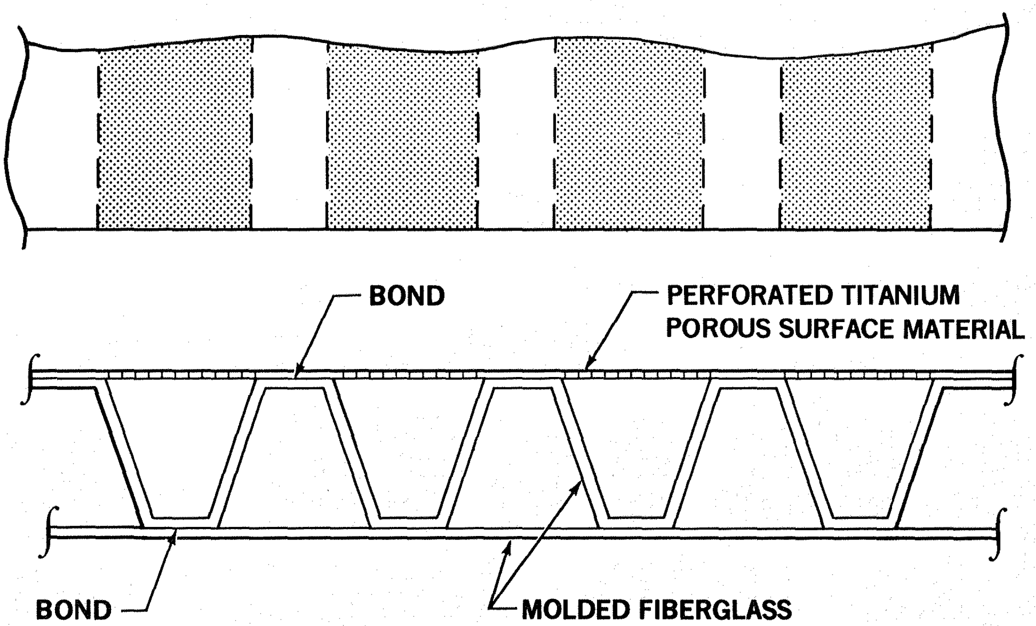


FIGURE 4-11. LFC GLOVE PANEL STRUCTURE

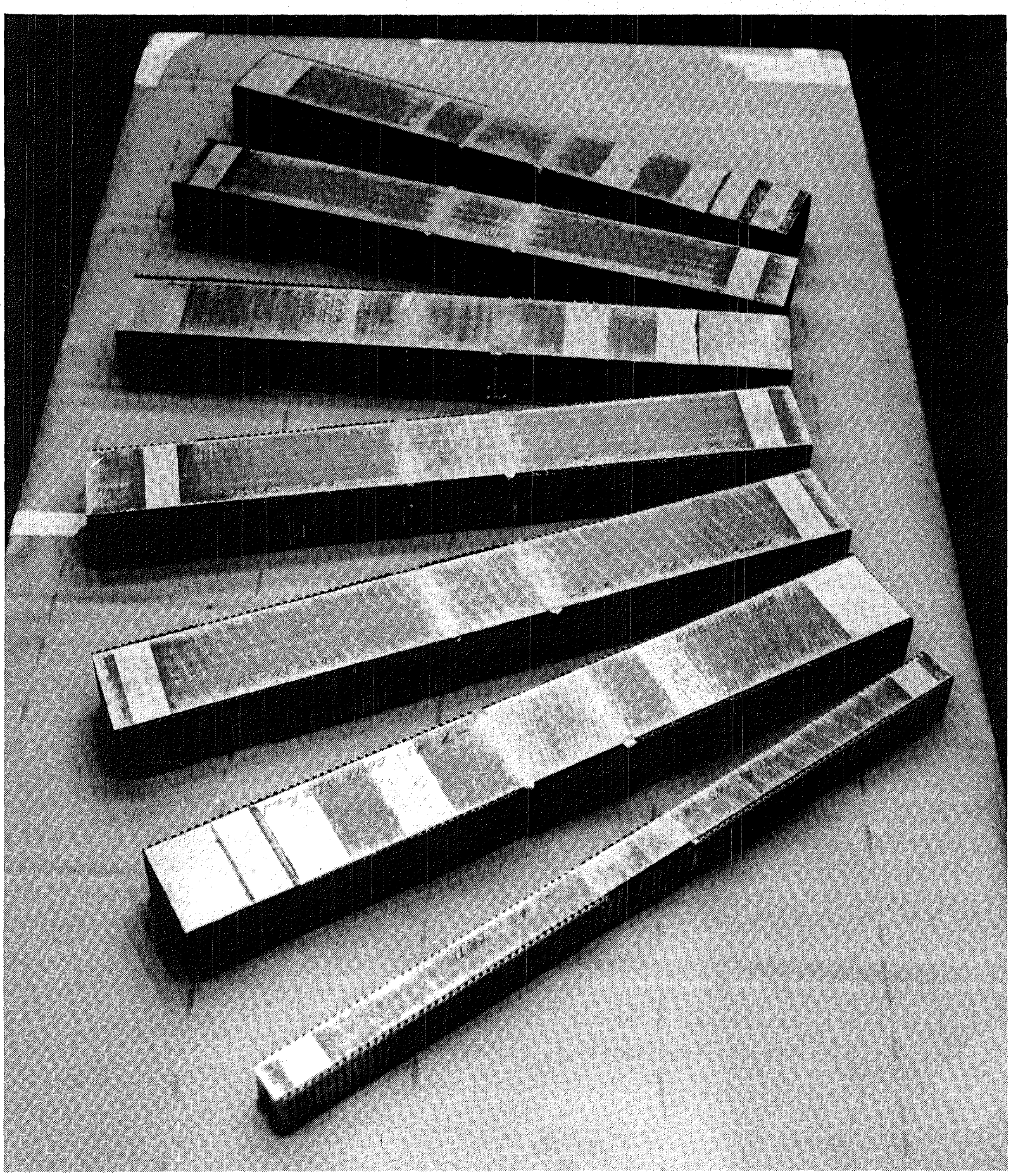


FIGURE 4-12. ELECTRON-BEAM-PERFORATED TITANIUM SHEET FATIGUE SPECIMENS

The ultimate strain level of Dynapore made from Nitronic 50 stainless steel exceeded 0.004, and the limit of proportionality exceeded 0.0027 strain, as shown in Figure 4-13. The static strength and strain characteristics of EB-perforated 6AL4V titanium were virtually the same as for the basic 6AL4V material. Thus both materials exhibited acceptable strain characteristics compatible with a carbon-fiber/epoxy primary structure.

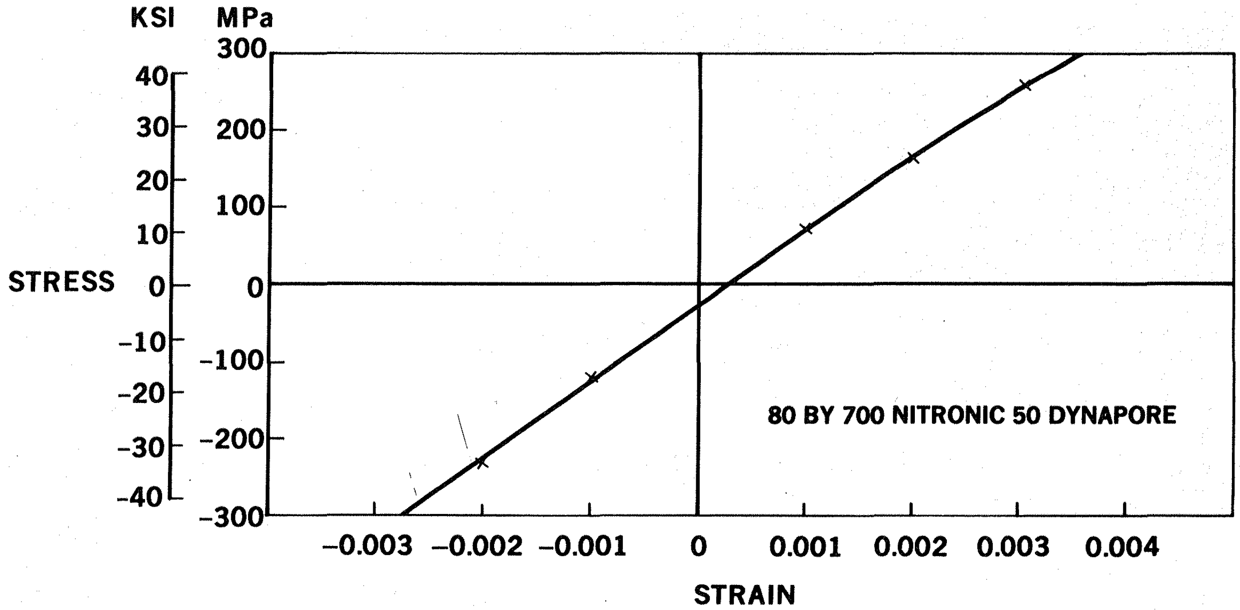


FIGURE 4-13. STRESS-STRAIN CURVE, NITRONIC 50 DYNAPORE

The fatigue test results are presented in Figure 4-14, and they show that the design requirement was exceeded by both materials.

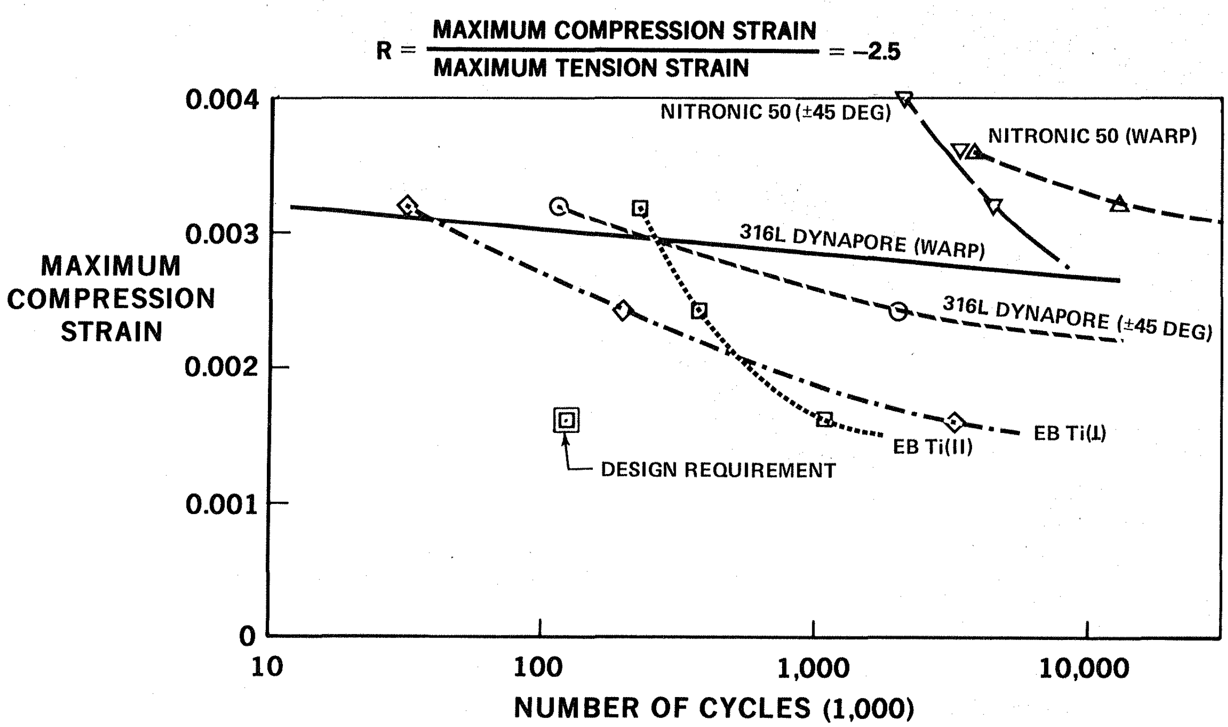


FIGURE 4-14. POROUS SURFACE FATIGUE

Dynapore is less satisfactory with respect to impact resistance. The curves in Figure 4-15 show that even with a secondary layer of 0.63-mm (0.025-in.) thick stainless steel sheet diffusion-bonded to the Dynapore, its impact resistance is less than that of a much lighter single layer of 0.63-mm (0.025-in.) thick EB-perforated titanium material. The perforated titanium sheet was also more resistant than the 1.86-mm (0.050-in.) thick 7075-T6 aluminum alloy sheet material commonly used for leading edges.

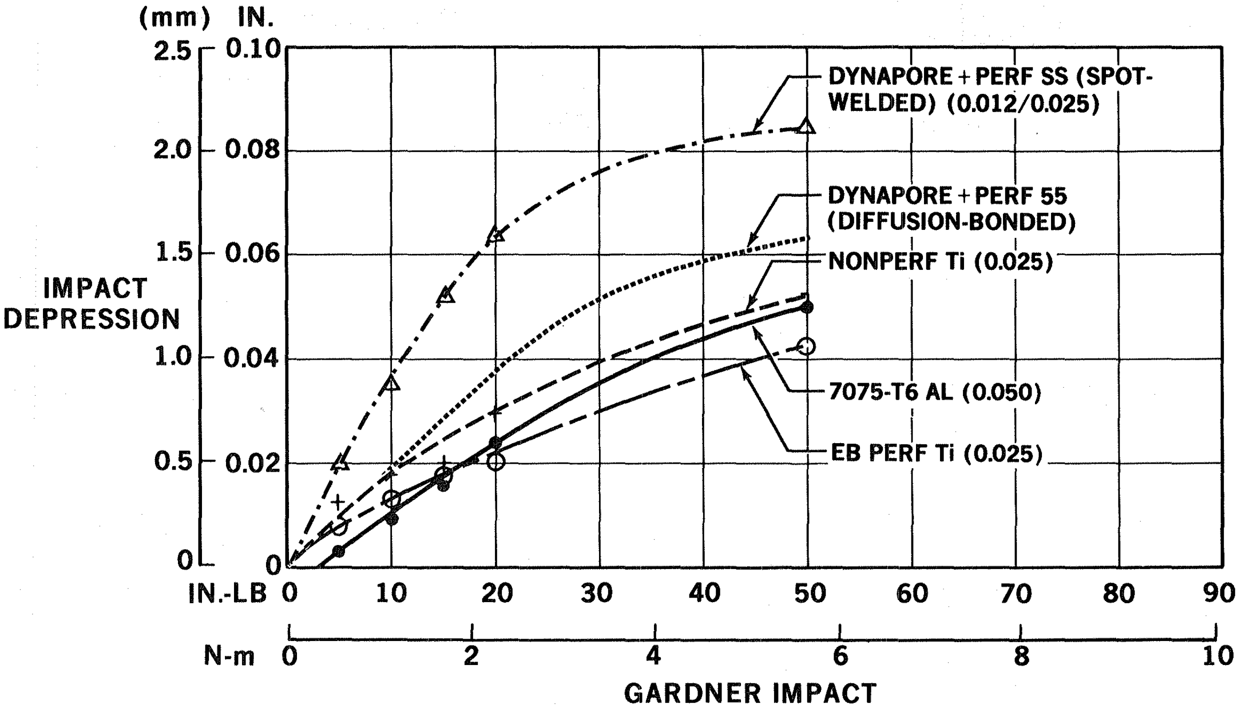


FIGURE 4-15. IMPACT-RESISTANCE COMPARISONS

Rain erosion testing was done using the whirling arm equipment at Wright Patterson AFB. The specimens were subjected to a simulated rainfall of 25.4 mm (1.0 in.) per hour at speeds up to 224 m/s (500 mph). At the highest speeds, the Dynapore surface tended to disintegrate and to be driven into the holes in the sublayer, as shown in Figure 4-16. The Dynapore rain erosion resistance was unsatisfactory but could have been improved by using the more finely perforated diffusion-bonded sublayer. The perforated titanium surface was unaffected by rain erosion at 179 m/s (400 mph) for 2 hours but slight bowing of the unsupported region occurred after exposure at 500 mph for 1 hour. This could be improved by narrowing the unsupported width at the leading edge.

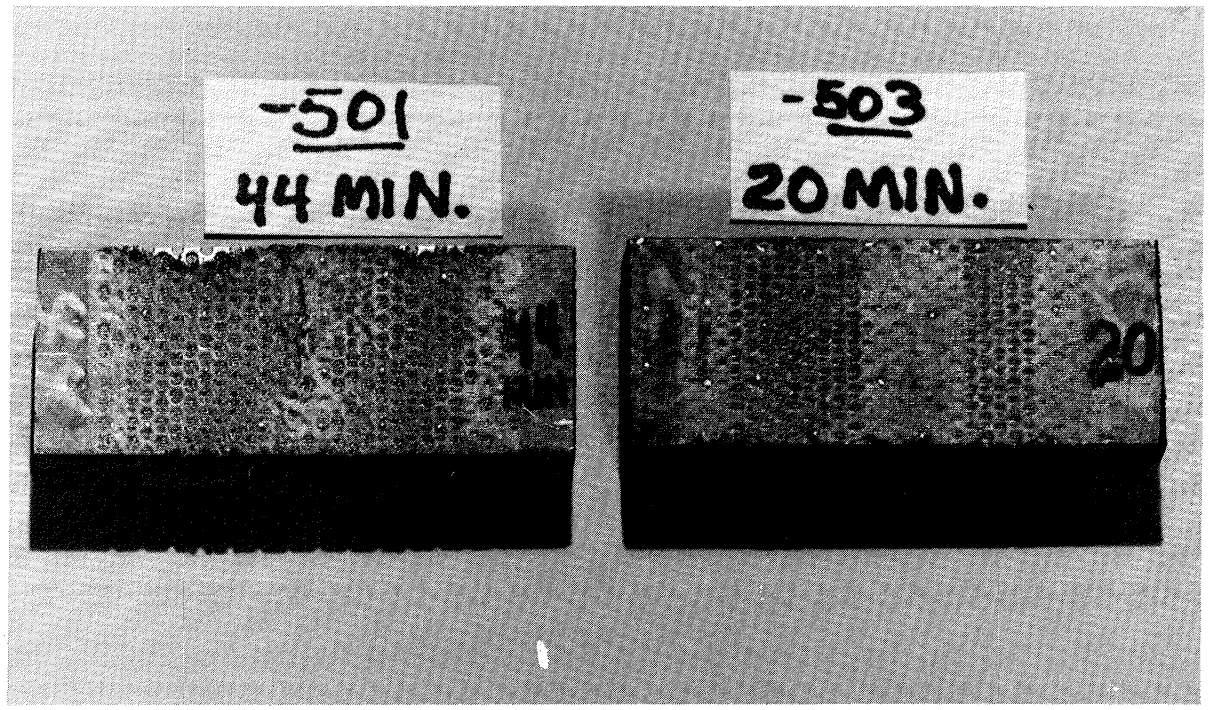


FIGURE 4-16. DYNAPORE RAIN EROSION SPECIMEN

Final Surface Selection

The electron beam-perforated titanium surface was finally selected for LFC. Compared with alternative suction surfaces, it offered the following advantages as verified by fabrication development and testing:

- Smooth LFC suction surface
- Simple low-weight construction
- Easily fabricated to obtain an accurate contour
- Reliable uniform porosity
- Porosity unaffected by stress
- Occasional steam cleaning maintains porosity
- Strength and stiffness compatible with primary structure
- LFC surface contributes to strength and stiffness in bending and torsion
- Resistant to corrosion
- Resistant to accidental damage
- Resistant to rain erosion.

LFC Panel Fabrication

The LFC panel is fabricated by moulding it against an accurate tool surface in an autoclave in two stages.

Stage 1. A silicone rubber mold is located on the tool surface, as shown in Figure 4-17A. The fiberglass preimpregnated material is then draped over the rubber mold and forced into the required corrugated form using additional rubber mandrels. Additional layers of fiberglass are wrapped over this combination and prepared for curing under heat and pressure in the autoclave (Figure 4-17B) to produce the supporting structure for the LFC surface.

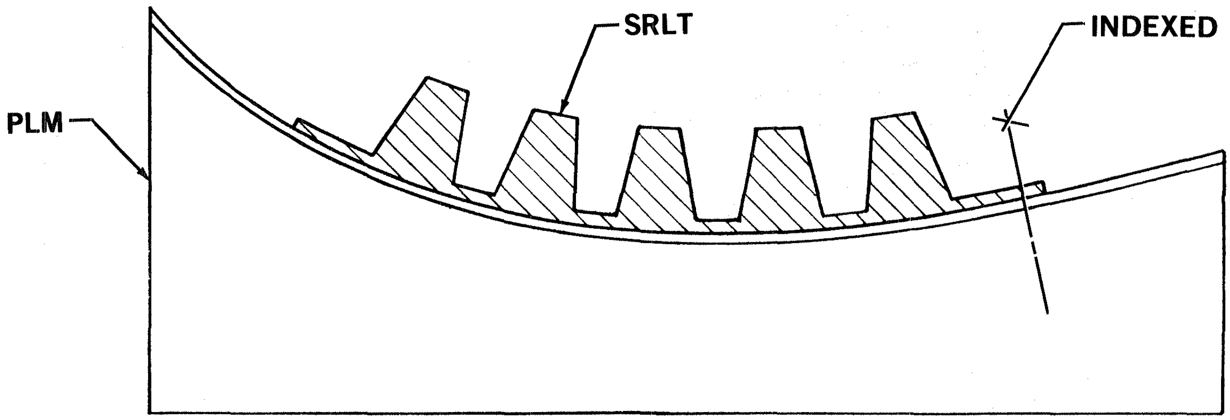


FIGURE 4-17A. BASIC SILICONE RUBBER TOOL

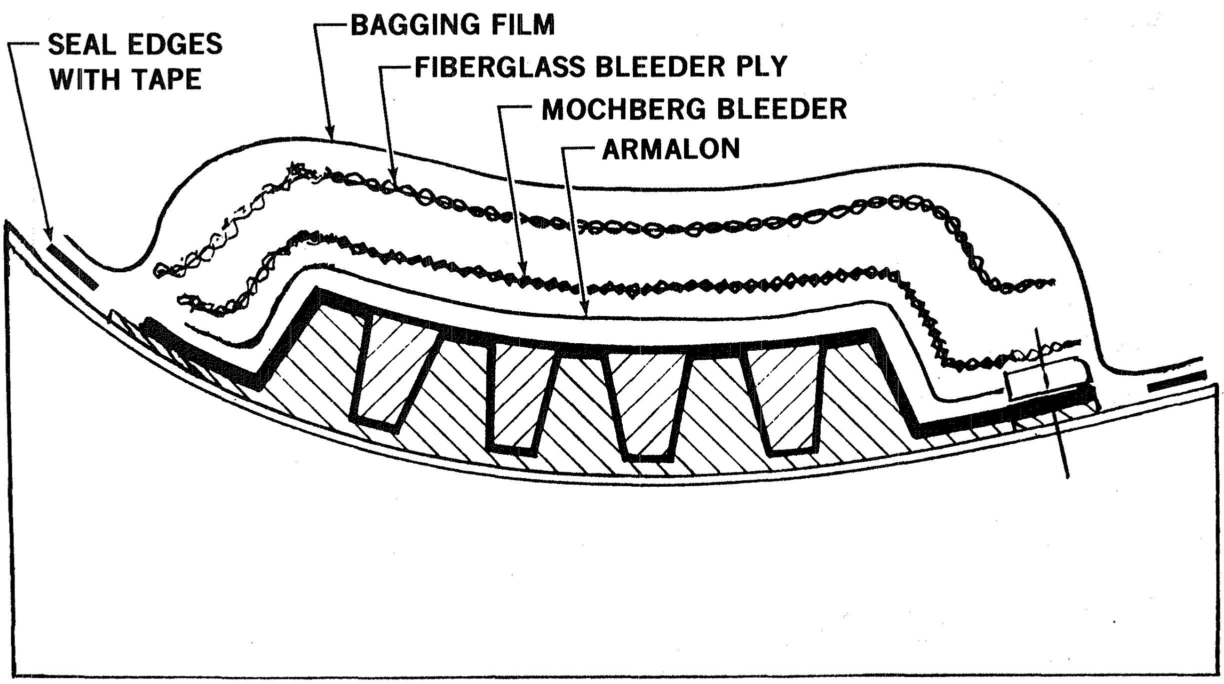


FIGURE 4-17B. BAGGING FOR AUTOCLAVE CURE CYCLE

Stage 2. The perforated titanium is located on the tool surface and bonded to its supporting structure, as shown in Figure 4-17C. The resulting LFC panel is illustrated in Figure 4-17D. Figure 4-18 shows the substructure for an LFC wind tunnel panel being laid up on the form tool and Figure 4-19 shows a completed leading edge for a 2.13-m (7-ft) chord wind tunnel model.

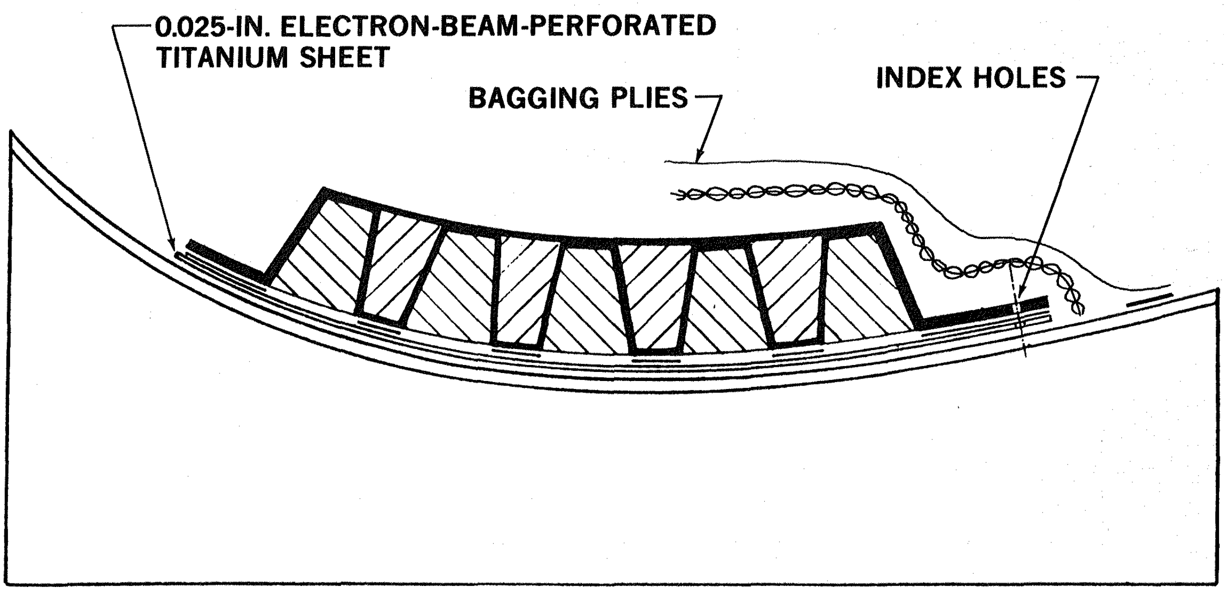
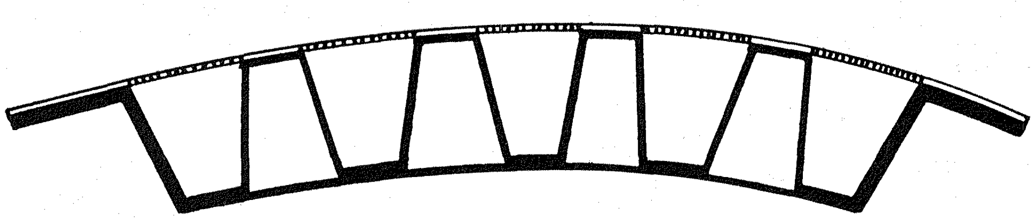


FIGURE 4-17C. BONDING OF TITANIUM FACE SHEET TO SUBSTRUCTURE



- ACCURATE REPRODUCTION OF THE MOLD SHAPE
- LESS THAN 0.001-INCH-AMPLITUDE SURFACE WAVINESS
- GOOD LAMINATE QUALITY

FIGURE 4-17D. COMPLETED PANEL

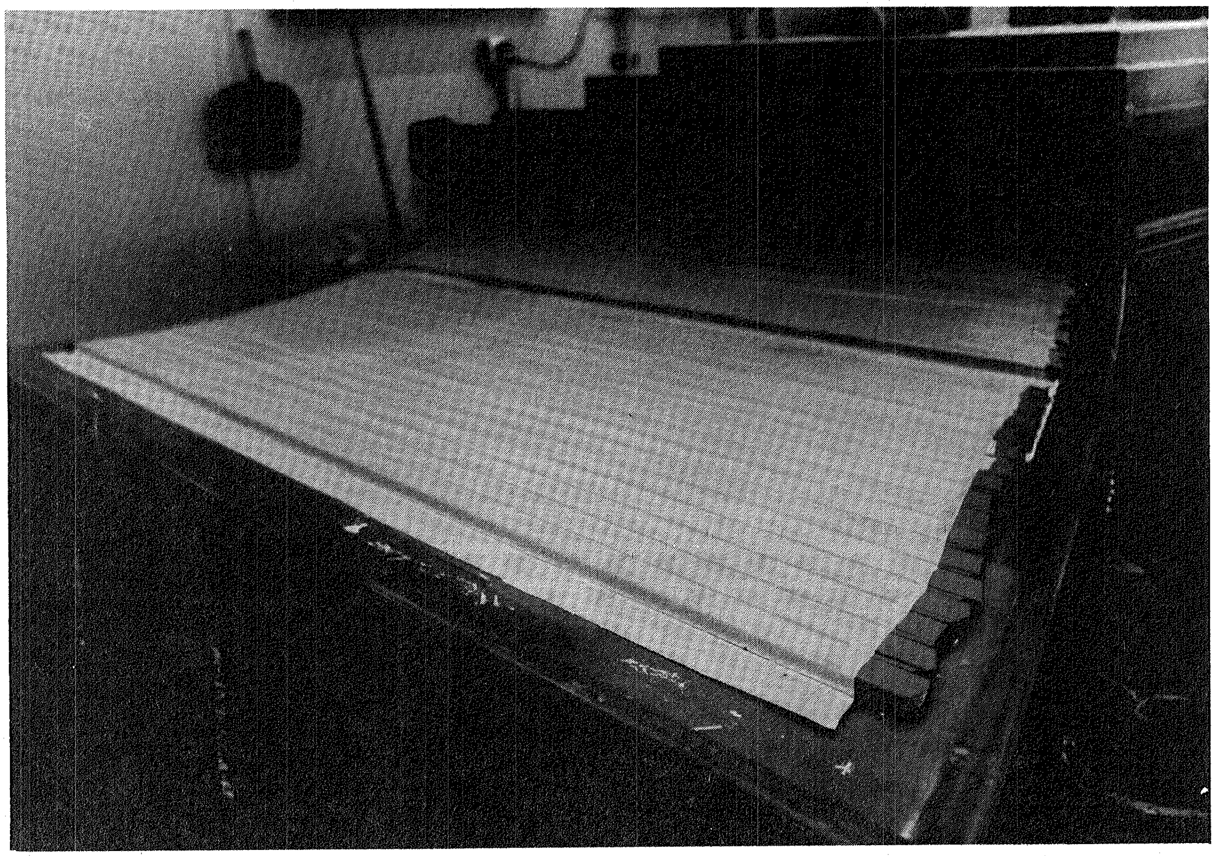


FIGURE 4-18. WIND TUNNEL MODEL SUBSTRUCTURE IN MOLDING FORM TOOL

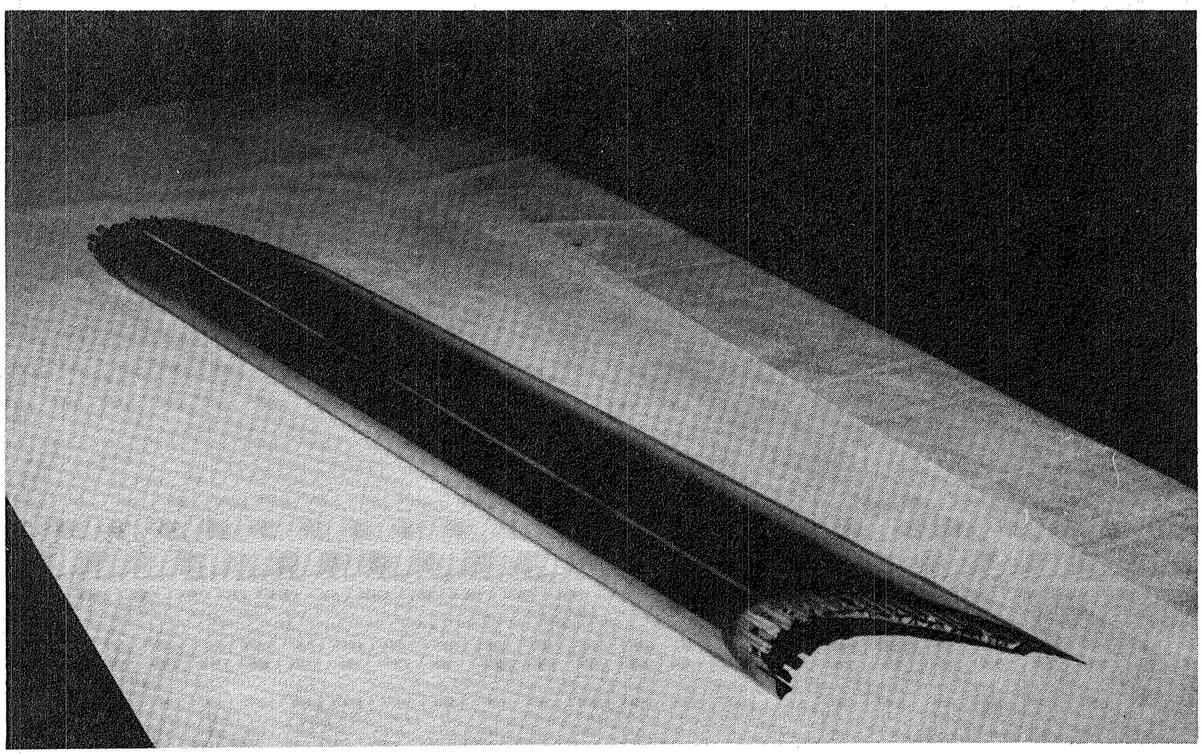


FIGURE 4-19. TITANIUM SURFACE BONDED TO SUBSTRUCTURE

Alternative LFC Panel Fabrication

A superplastic-formed/diffusion-bonded (SPFDB) all-titanium panel substructure was produced to investigate this alternative to molded fiberglass or carbon-fiber/epoxy substructures. The panel is shown in Figure 4-20. The inner walls create integral ducts for the suction airflow. Dimples formed in the channels of the upper surface can be machined to form multiple holes to transfer the airflow from the surface to the ducts. To complete the LFC panel, perforated titanium is bonded to the upper surface. The results of this fabrication experiment (Reference 3) were encouraging but efforts were concentrated on the molded substructure because the high cost of SPFDB tooling was not warranted for the limited production of LFC experimental panels at this time.

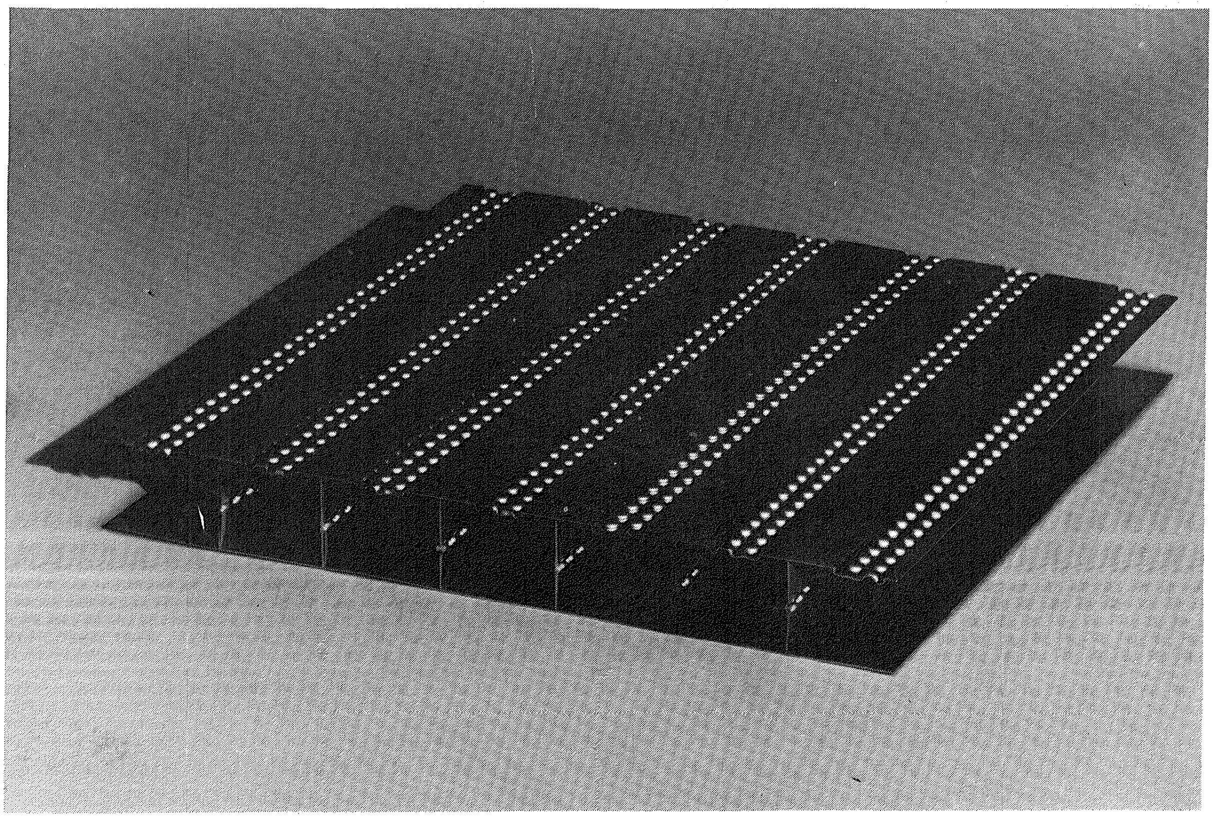


FIGURE 4-20. SUPERPLASTIC-FORMED/DIFFUSION-BONDED TITANIUM SANDWICH PANEL BEFORE MACHINING

5. LFC SWEPT-WING WIND TUNNEL TESTING

Possible LFC surfaces were tested initially to determine their comparative effectiveness for LFC under predominantly Tollmein-Schlichting instability conditions, as described earlier in Section 4. It was then necessary to build a swept-wing wind tunnel model to test the selected porous surfaces under cross-flow conditions.

The model chord was 2,135 mm (7 ft), the span was 1,370 mm (4.5 ft), and the sweep angle was 30 degrees. The airfoil section was designed to achieve the desired LFC pressure distribution on the upper surface, allowing for tunnel walls, and liners were installed to approximate infinite aspect ratio conditions. Trailing edge flaps in three sections were used to finally adjust the pressure distribution. The LFC test panels were removable, as shown in Figure 5-1, so that alternative LFC surfaces could be tested. Figure 5-2 shows a section through the Dynapore test panels. Sections through electron beam-perforated titanium leading edges are shown in Figure 5-3. The photograph of the partly completed model shows the form of construction (Figure 5-4). Flexible tubing was used to connect the suction flutes in selected groups to a number of plenum chambers with individual flow control valves, as shown in Figure 5-5.

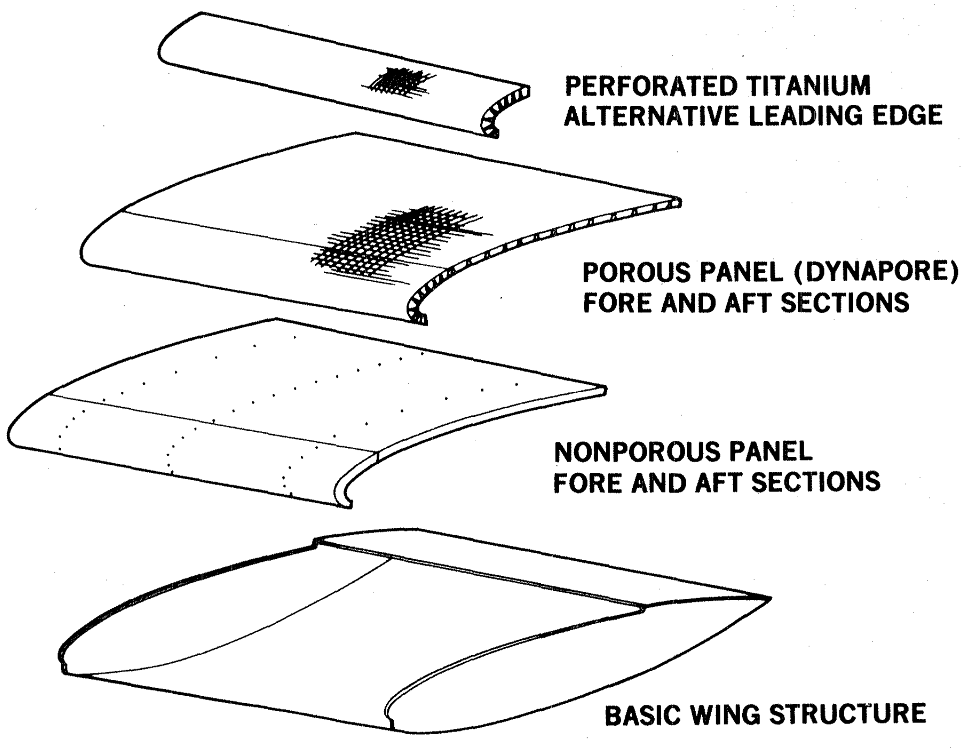


FIGURE 5-1. LFC SWEPT-WING MODEL TEST COMPONENTS

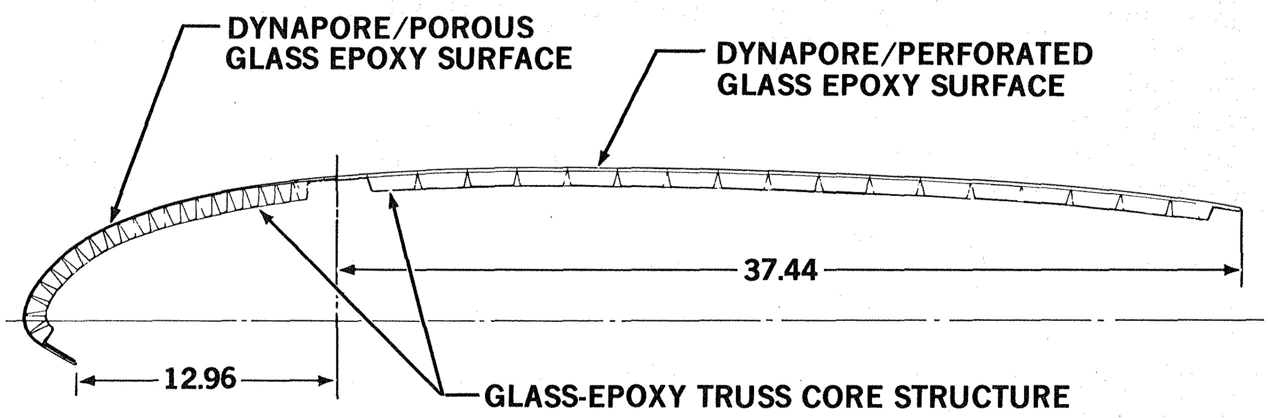


FIGURE 5-2. WIND-TUNNEL MODEL LFC SURFACE

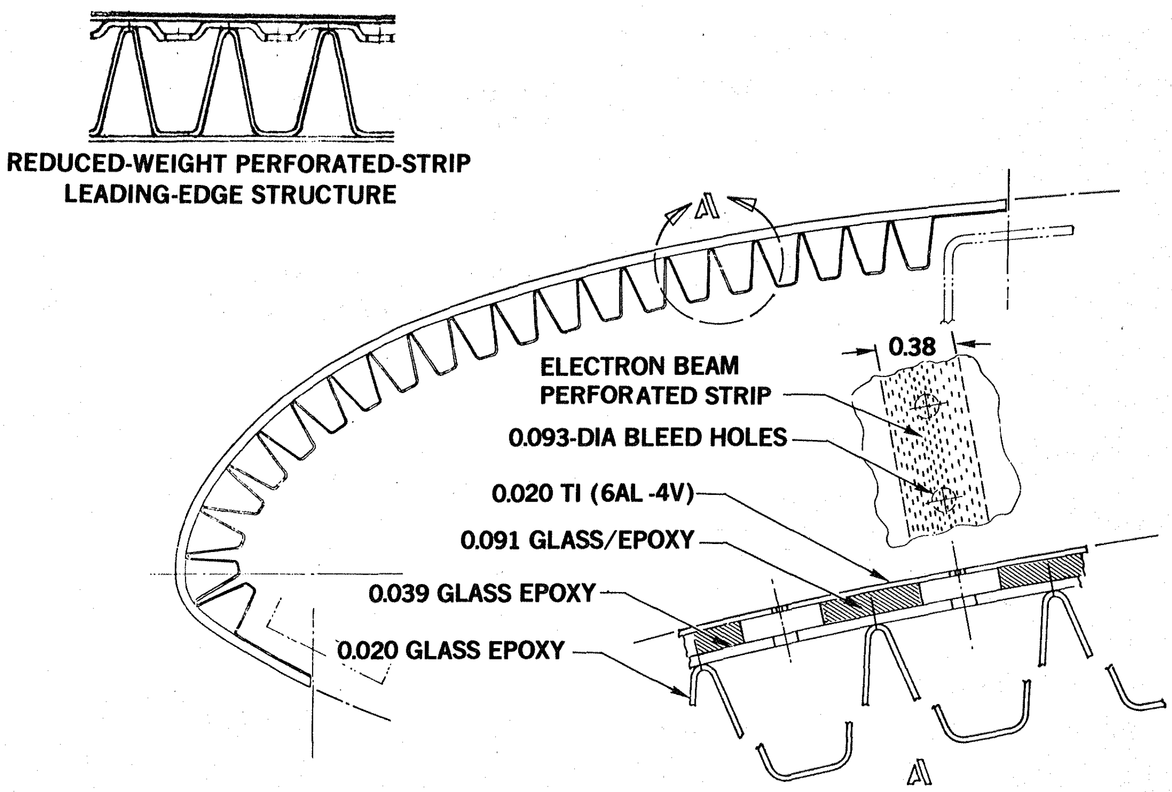


FIGURE 5-3. LEADING EDGE STRUCTURE WITH TITANIUM SURFACE

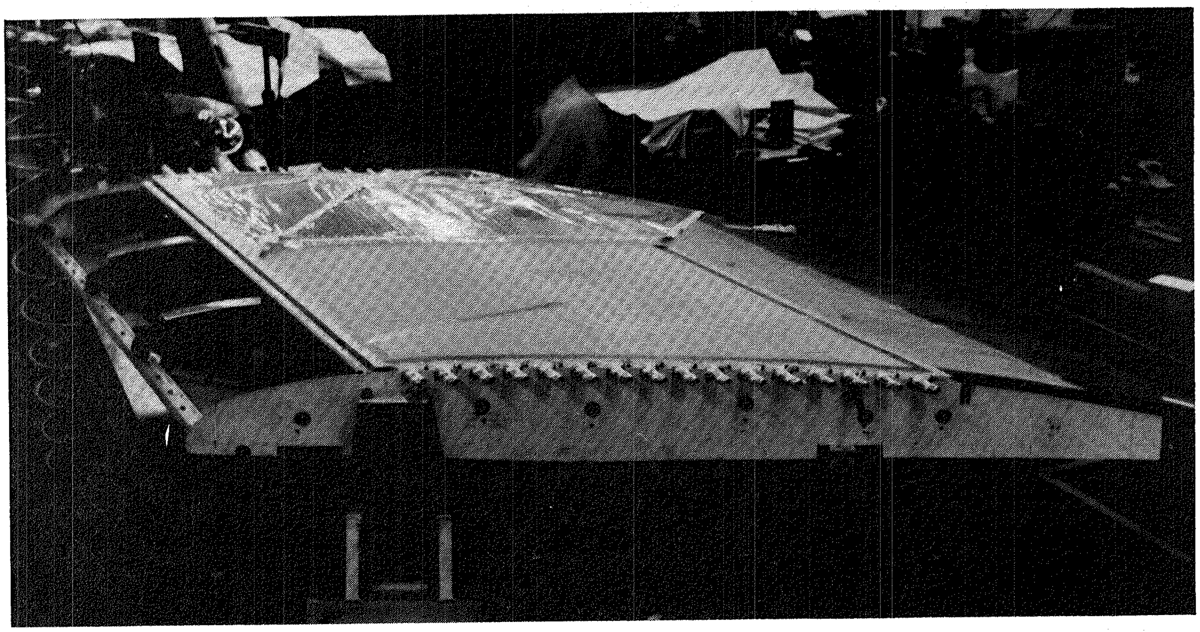


FIGURE 5-4. SWEPT WING MODEL POROUS TEST PANEL

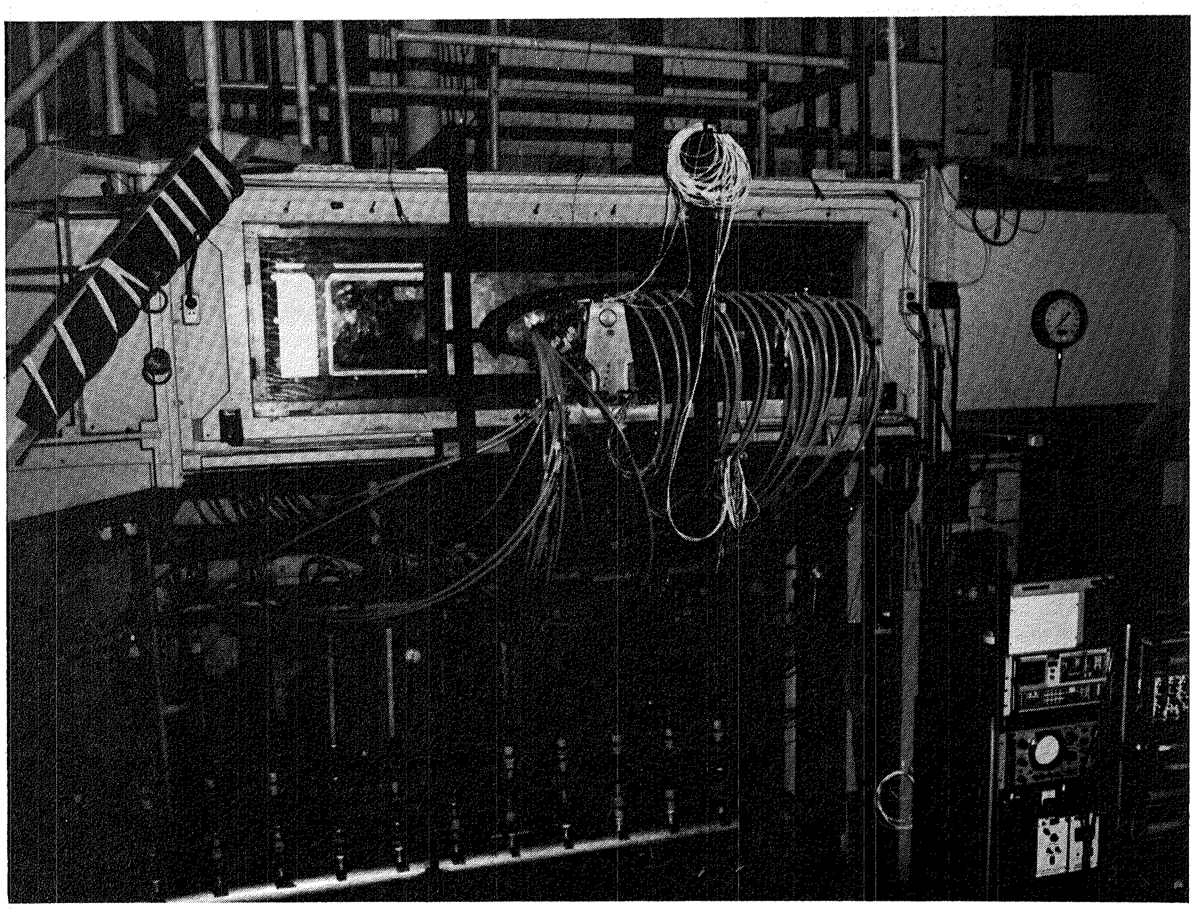
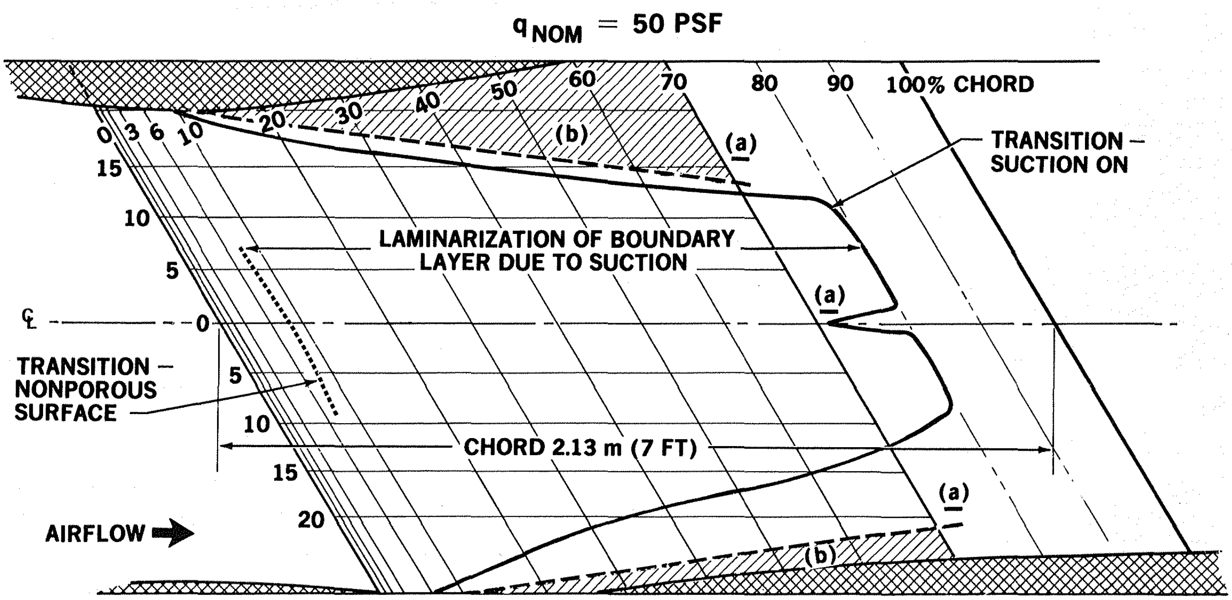


FIGURE 5-5. WIND TUNNEL MODEL TEST SETUP

Natural laminar flow occurred to about 8-percent chord. With suction back to the full extent of the suction region at 70-percent chord, laminar flow was obtained to 80-percent chord, as illustrated in Figure 5-6. This was achieved with the Dynapore surfaces and the electron beam-perforated titanium leading edge section.



(a) TOTAL HEAD PROBES 10 mm (0.40 IN.) ABOVE SURFACE
(b) NONPOROUS SIDEWALL WEDGES

FIGURE 5-6. EFFECT OF SUCTION TO 70 PERCENT CHORD ON TRANSITION

6. INITIAL LFC AIRCRAFT STUDY

DESIGN MISSION

An aircraft with payload and range characteristics similar to a DC-10-30 was selected for the study. The primary requirements were:

Range	9,260 km (5,000 n mi)
Payload	300 passengers
Cruise Mach number	0.8
Approach speed	67 m/s (130 kn)
Field length	3,048 m (10,000-ft)

FACTORS AFFECTING CONFIGURATION

Airfoil Sections

Since is it unlikely that laminar flow can be maintained behind a shock wave downstream of the supersonic flow region, the LFC airfoil was required to be shock-free. The aft pressure recovery gradient was restricted to avoid buffet and increased drag due to flow separation with either laminar or turbulent flow conditions. This would allow the continuation of satisfactory cruising flight following a possible loss of LFC due to environmental conditions or system failure. Typical pressure distributions for airfoils meeting these requirements are shown in Figure 6-1. For different airfoil thicknesses, the upper surface pressure distribution remains constant and the lower surface pressure distribution is adjusted to provide the required design section lift coefficient.

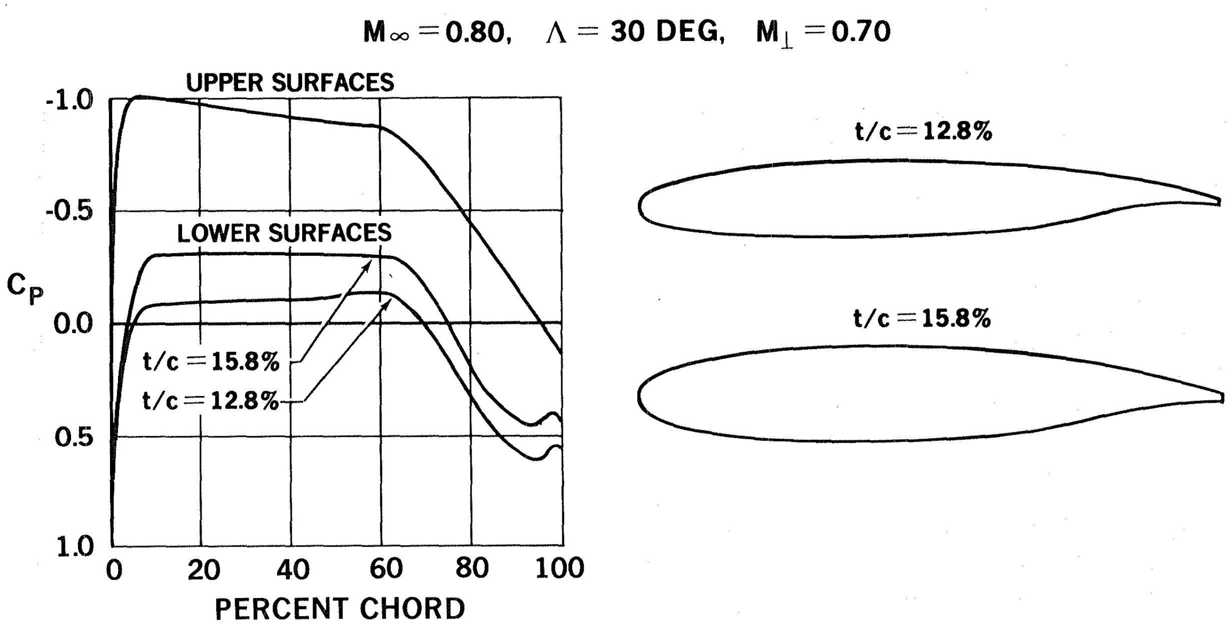


FIGURE 6-1. TYPICAL DESIGN PRESSURE DISTRIBUTIONS AND AIRFOIL SHAPES

The LFC requirements result in a significant reduction in allowable wing thickness, as illustrated in Figure 6-2. A comparison of LFC and turbulent airfoil sections is shown in Figure 6-3.

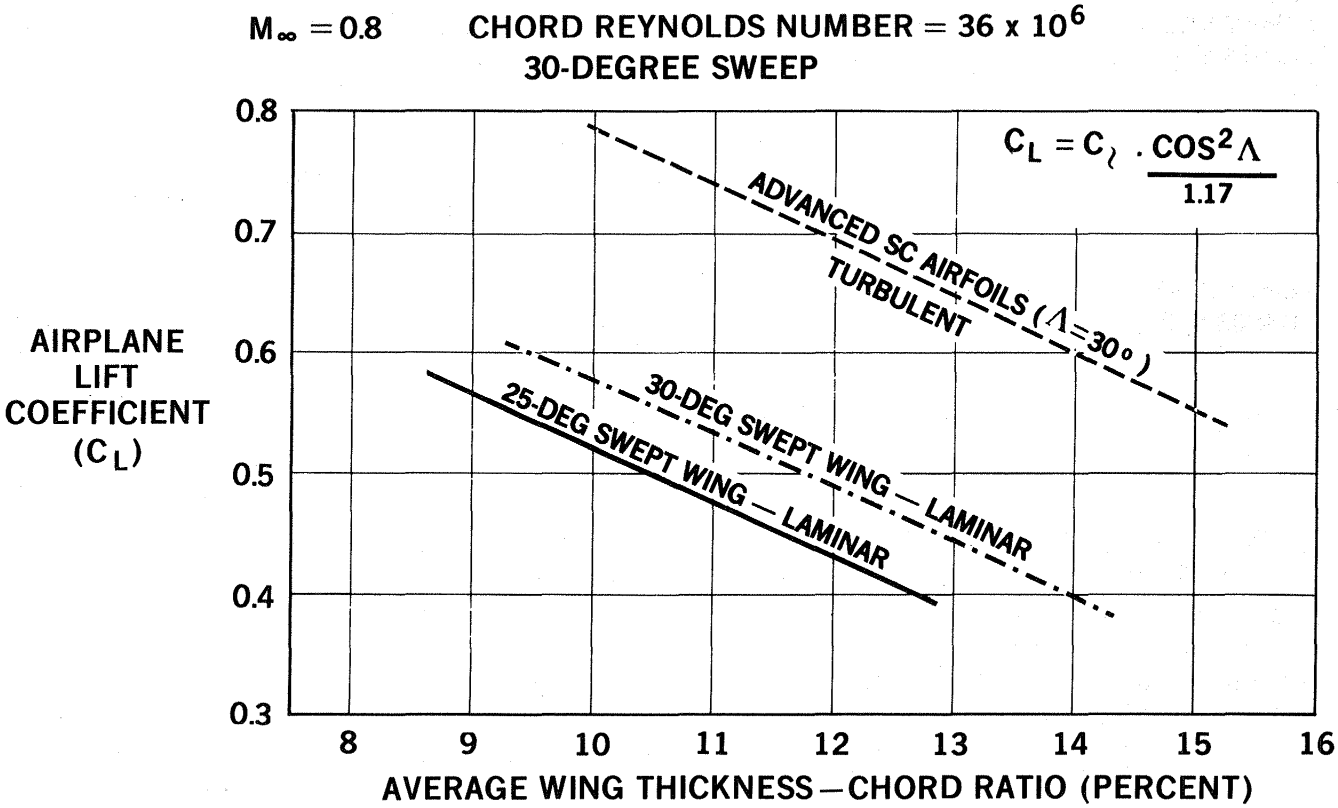


FIGURE 6-2. VARIATION OF DESIGN LIFT COEFFICIENT WITH AIRFOIL THICKNESS

Suction Requirements

The suction requirements for the upper and lower surfaces are illustrated in Figures 6-4A and 6-4B, respectively. Depending primarily on the leading edge radius and the sweep angle, suction may be required to prevent flow instability due to spanwise flow along the leading edge. In the leading edge region, suction is also required to overcome instabilities due to a steep pressure gradient combined with swept isobars. Further aft, extending as far as the pressure recovery region, Tollmien-Schlichting instabilities predominate and the suction requirements are low. In the aft pressure recovery region, cross-flow conditions again occur; the required high level of suction is influenced by the chord Reynolds number, as shown.

Propulsion Engine Location

The influence of engine-generated noise on LFC performance was considered. Figure 6-5A is an acoustic map of OASPL in terms of dB relative to 0.02 mPa (0.0002 dyne/cm^2) for an E^3-type engine in cruising flight conditions. Figures 6-5B and 6-5C show the corresponding noise levels for four-engined aircraft configurations with engines located under the wing and on the aft fuselage, respectively. Based on X-21 air-

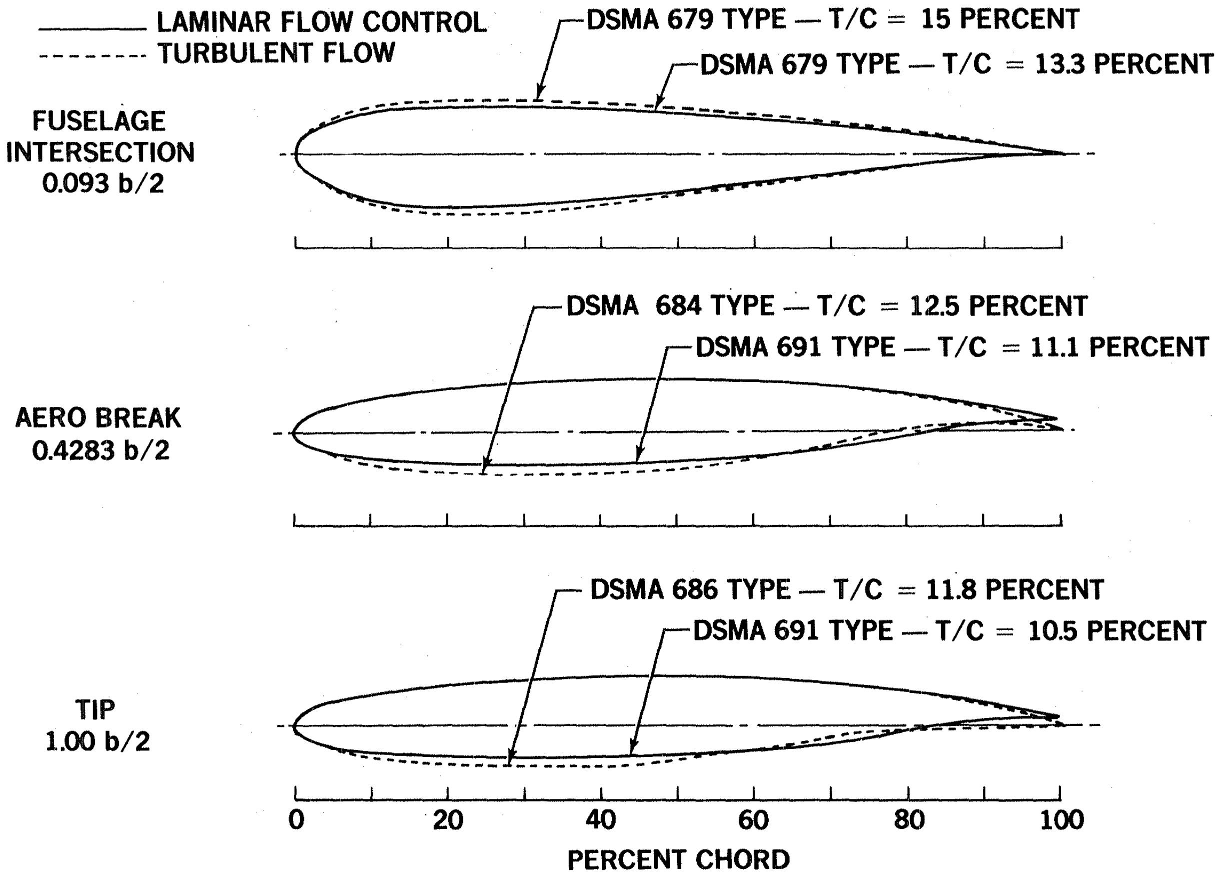


FIGURE 6-3. ASSUMED BASE CASE AIRFOILS

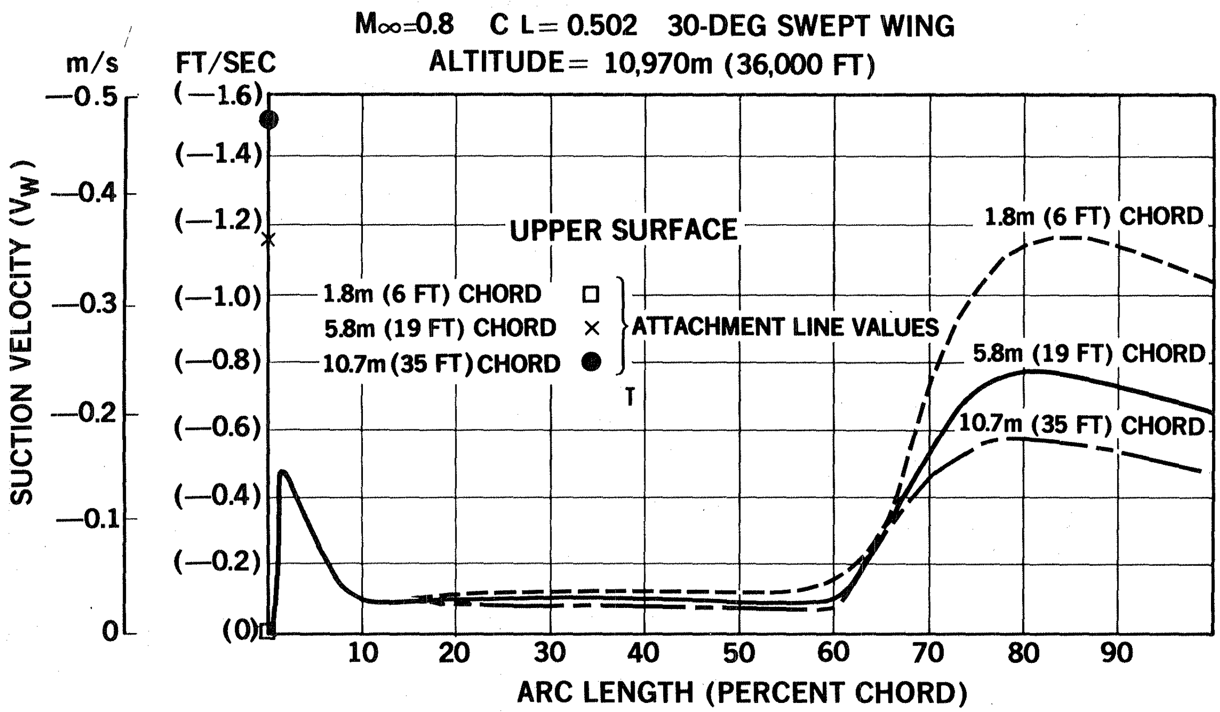


FIGURE 6-4A. TYPICAL SUCTION DISTRIBUTIONS – UPPER SURFACE

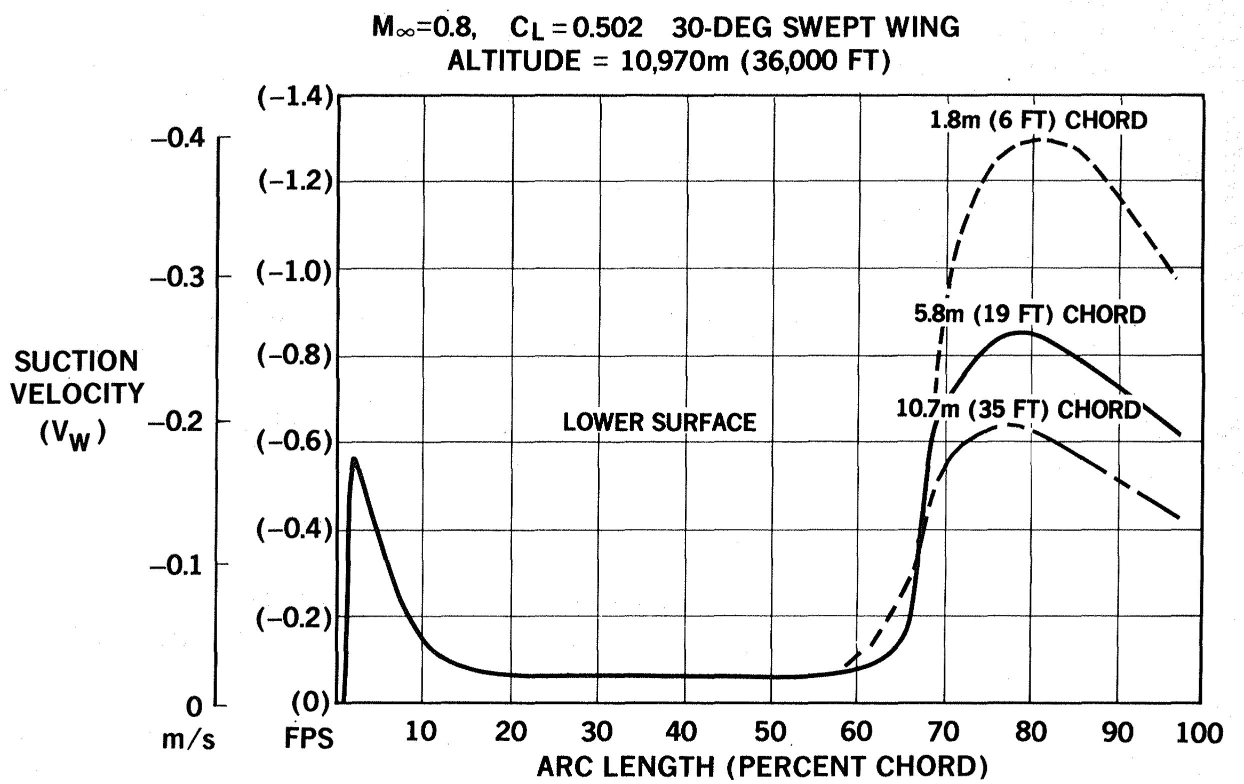


FIGURE 6-4B. TYPICAL SUCTION DISTRIBUTIONS – LOWER SURFACE

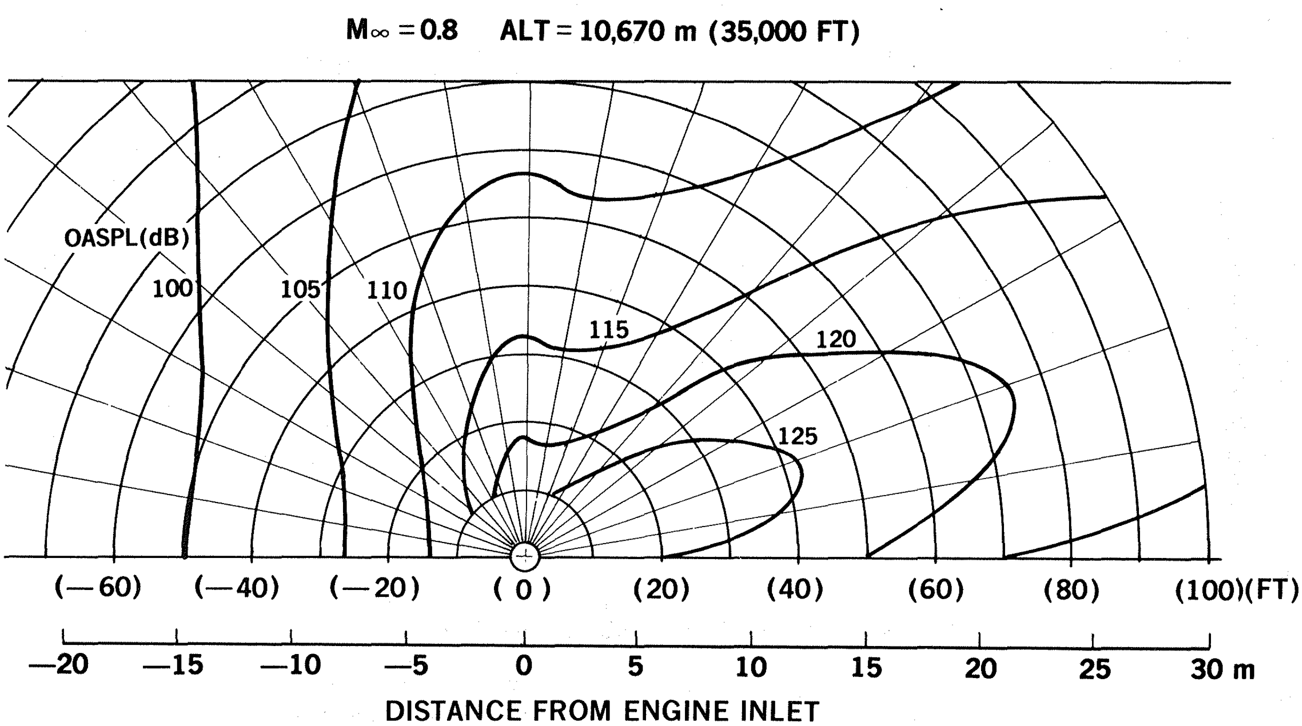


FIGURE 6-5A. NEAR-FIELD ACOUSTIC ENVIRONMENT DUE TO ONE ENGINE

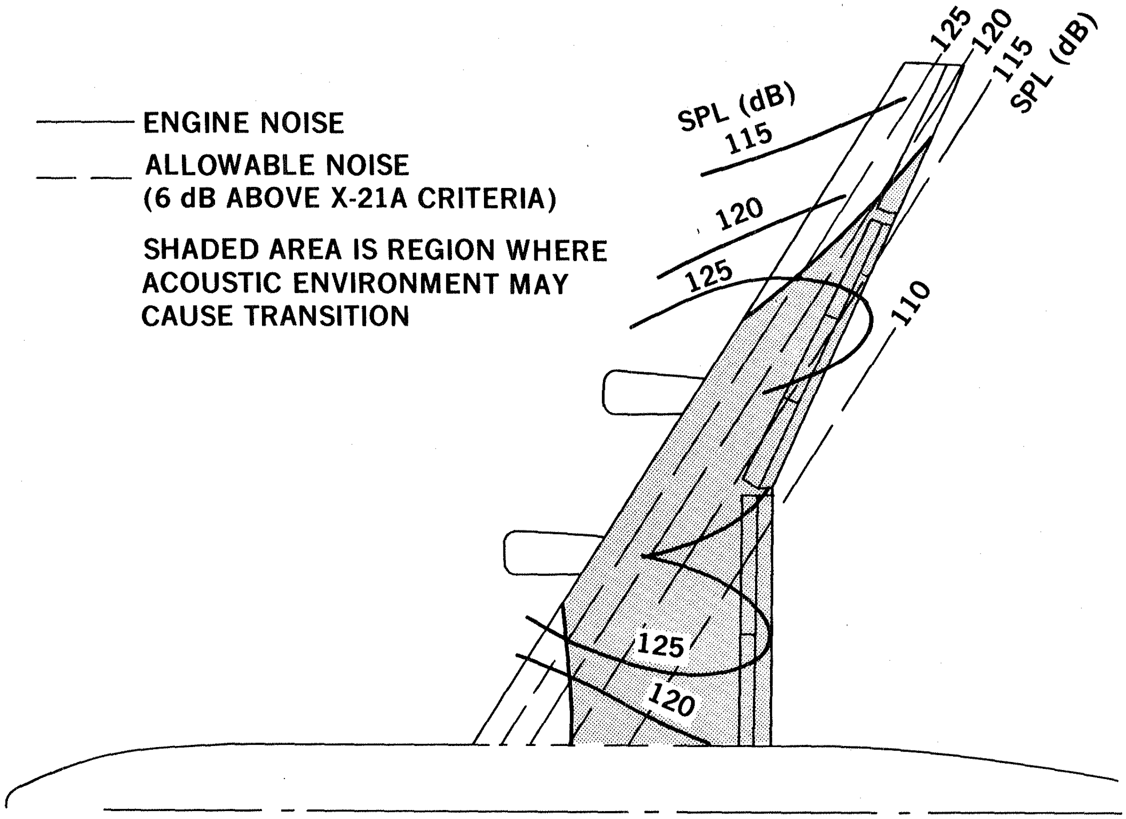


FIGURE 6-5B. EFFECT OF ENGINE-INDUCED ACOUSTIC ENVIRONMENT ON EXTENT OF LFC (WING-MOUNTED ENGINES)

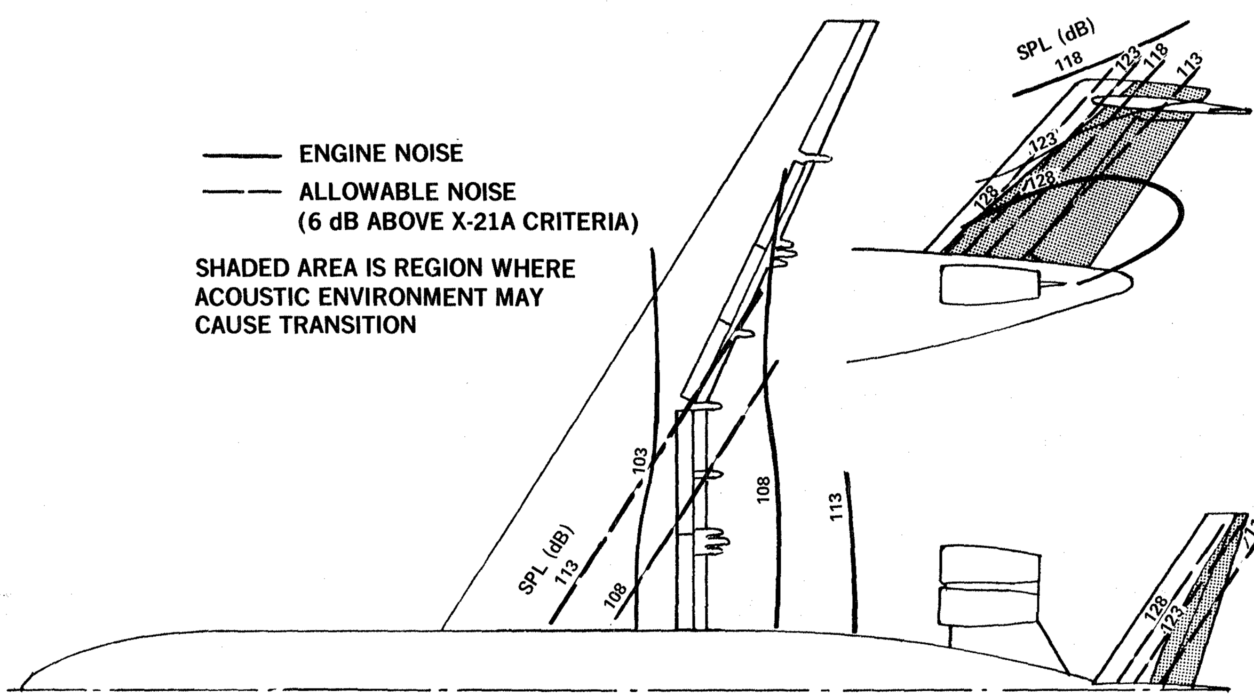


FIGURE 6-5C. EFFECT OF ENGINE-INDUCED ACOUSTIC ENVIRONMENT ON EXTENT OF LFC (FUSELAGE-MOUNTED ENGINES) craft criteria, the wing-mounted engines would result in an unacceptable noise level at the LFC wing surface. Aft fuselage-mounted engines were therefore selected. Excessive noise levels would then occur over most of the tail unit, so LFC was limited to the wing surfaces only.

Suction Pump Location

The desirable maximum duct velocity to keep duct losses and internal noise generation within reasonable limits is about 0.2 M. However, duct size is limited by the space available within the wing. It was possible to meet these requirements using one suction pump on each side by mounting the pump and motor units under the wing at spanwise locations where the suction airflows were equal in both directions. This is illustrated by Figure 6-6 which shows that minimum duct size is achieved with the suction units located at 42 percent of the semispan. The figure also shows that the minimum duct pressure allotted would be exceeded even with twice the anticipated duct pressure losses. The suction units were finally located close to the optimum position at the trailing edge wing break point, as shown in Figure 6-7, in order to simplify the flap system.

$$C_Q = \frac{V_W}{V_\infty} = 1.3 \times 10^{-4}$$

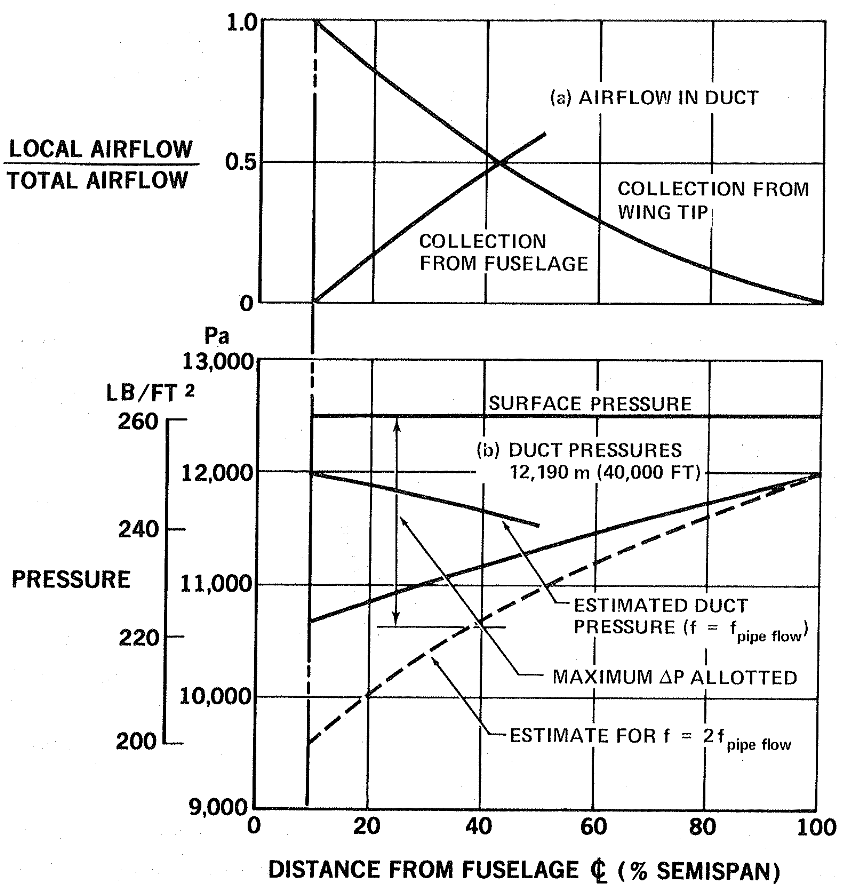


FIGURE 6-6. SUCTION AIRFLOW IN WING-BOX DUCTS

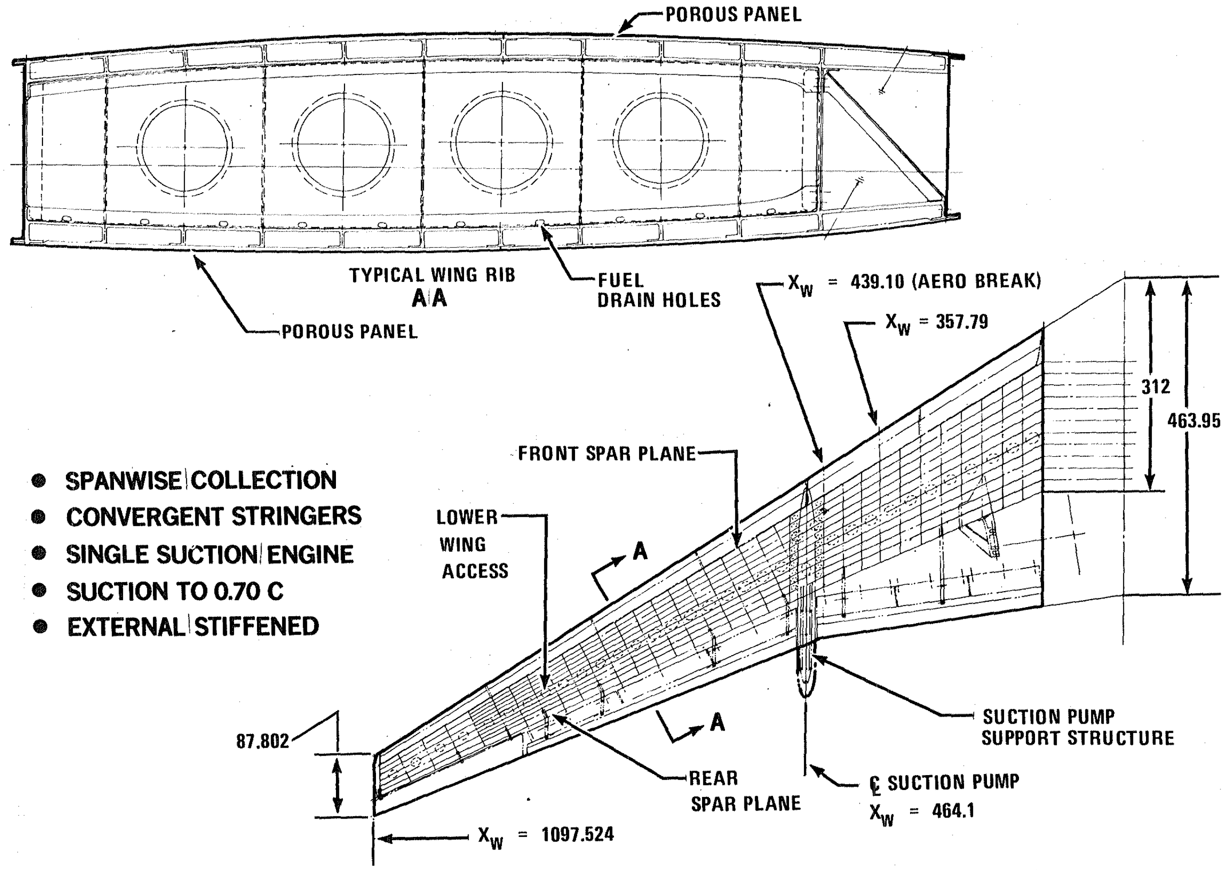


FIGURE 6-7. WING STRUCTURE

Wing Structure

Figure 6-7 also shows a plan of the wing structure and a typical rib. In this arrangement, the suction air flows through the porous glove panel and is transferred spanwise through integral ducts formed by the glove panel, the wing stiffeners, and the inner load-carrying skin. The latter provides a substantial barrier between the suction ducting and the integral fuel tank.

Due to the unconventional wing construction consisting of a porous glove outer panel and an inner carbon-fiber/epoxy main structural box, it was necessary to conduct a comprehensive wing design study. Wing strength, flutter speed, and aeroelastic effects on roll control were analyzed with wing aspect ratios ranging from 10 to 14. In all cases, structural sizing was determined by the wing bending stiffness needed to meet aeroelastic requirements. Figure 6-8 shows the resulting increased stiffness and wing weight over strength requirements as a function of aspect ratio. High-modulus GY-70 carbon fibers orientated to favor bending stiffness were introduced into the basic T-300 fiber laminate to achieve these results.

The influence of combinations of dissimilar materials with respect to thermal stresses and glove panel load intensity was analyzed. Figure 6-9 shows the secondary advantage of using carbon-fiber/epoxy material for the primary structure to reduce the stress level in the glove panel and to minimize the load transfer at any panel joints.

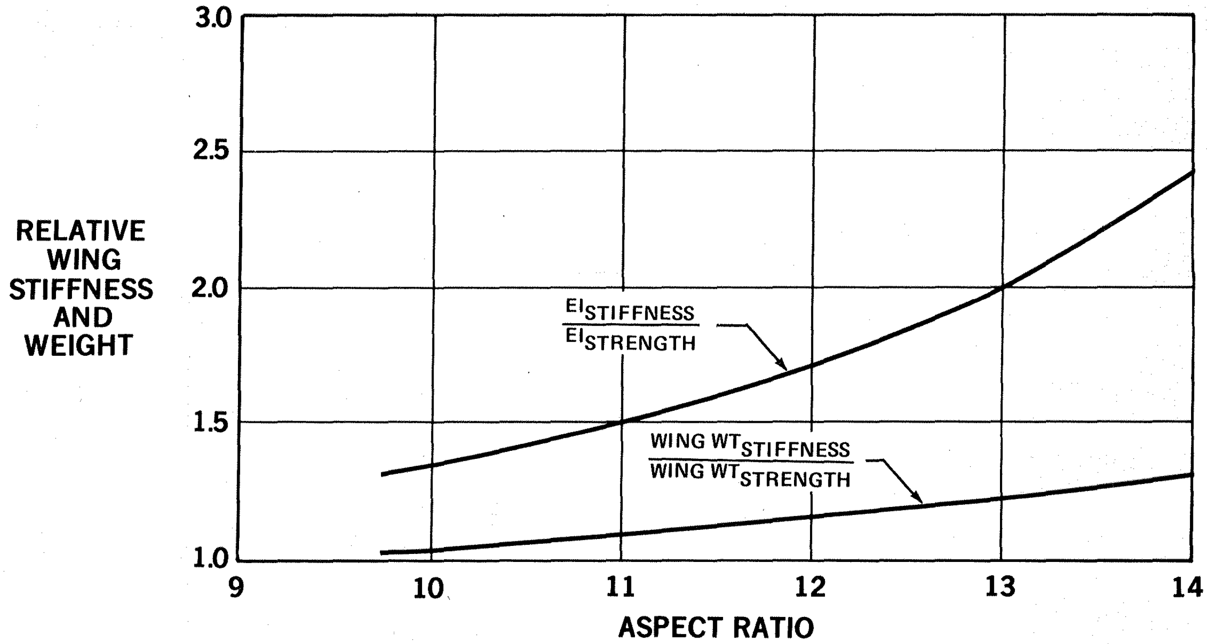


FIGURE 6-8. EFFECT OF ASPECT RATIO ON WING STIFFNESS AND WEIGHT

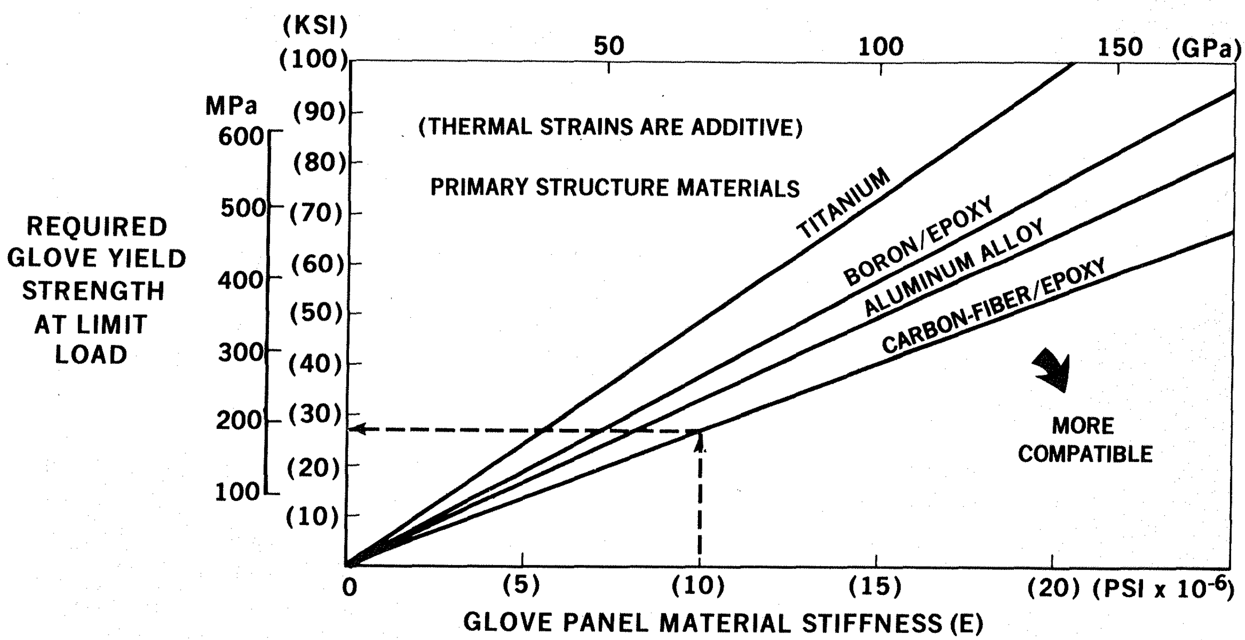


FIGURE 6-9. STRENGTH-STRAIN REQUIREMENTS FOR GLOVE PANELS

Panels combining a porous glove surface and a representative carbon-fiber/epoxy primary structure were tested satisfactorily under compression and shear loading conditions. A typical compression test is illustrated in Figure 6-10. The largest compression panel tested measured 2,070 by 730 mm (81.5 by 28.75 in.).

FIGURE 6-10. COMPRESSION PANEL TEST

INITIAL BASELINE LFC AIRCRAFT

Cruise Conditions

A step cruise-climb mission profile and international fuel reserves were assumed, in accordance with commercial operational rules. In this procedure, the aircraft cruises at a constant altitude until sufficient fuel has been used to allow the cruise altitude to increase by an increment of 1,219 m (4,000 ft). This is illustrated in Figure 6-11 which also shows the effect on operating C_L. The design C_L is that required for the initial cruise altitude. As fuel is burned the C_L falls off until the step climb results in a return to the design C_L. The effect of changing C_L at constant Mach number is illustrated in Figure 6-12. It shows that an increase in C_L above the design value could have an adverse effect on LFC but reducing the C_L is satisfactory.

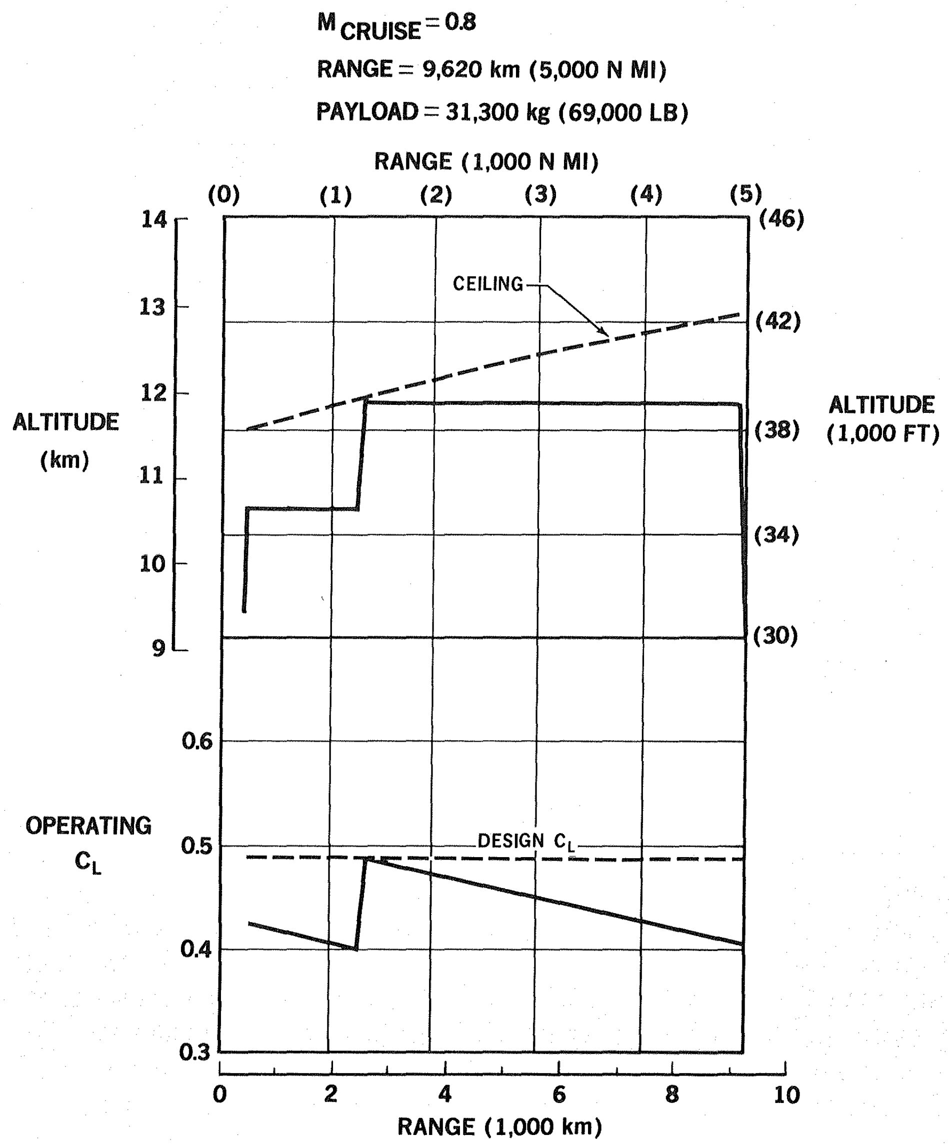


FIGURE 6-11. LFC AIRCRAFT ALTITUDE PROFILE

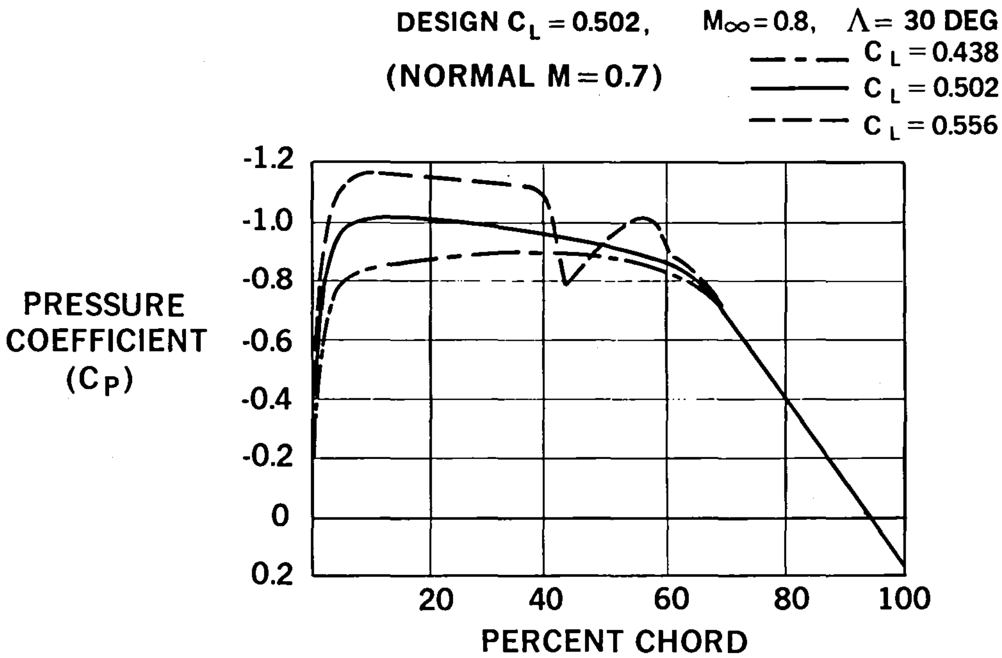


FIGURE 6-12. CHANGE OF AIRFOIL PRESSURE DISTRIBUTION WITH LIFT COEFFICIENT

An initial cruise altitude of 10,670 m (35,000 ft) was selected for operational flexibility with respect to air traffic control-assigned altitudes, and to reduce the probability of encountering ice crystals in the atmosphere that can cause temporary loss of LFC.

Analysis showed that a loss of LFC during cruise could result in a pressure distribution that would adversely affect the restoration of LFC. This is illustrated in Figure 6-13 which also shows that this effect can be counteracted by a small deflection of a trailing edge flap. It was assumed that an active flap of this type would be required on the LFC aircraft.

Aircraft Sizing

Component weights were estimated and sizing plots similar to that of Figure 6-14 were run for aspect ratios 10, 12, and 14. Takeoff gross weights were not significantly different for aspect ratios 10 and 12 but were appreciably greater at aspect ratio 14, probably due to the increased aeroelastic weight penalty discussed earlier under Wing Structure. Aspect ratio 10 was selected over 12 because this reduced the length of the suction ducting and allowed increased duct areas. Figure 6-14 also shows that for minimum takeoff gross weight, the initial cruise altitude would be less than 10,670 m (35,000 ft) and indicates the penalty for selecting this requirement. The penalty is largely due to the LFC airfoil limitations (described earlier under Airfoil Sections) which result in a reduction of cruise C_L (illustrated earlier in Figure 6-2). The selection of a higher initial cruise altitude to further reduce the probability of encountering atmospheric ice crystals would result in a corresponding increased weight penalty.

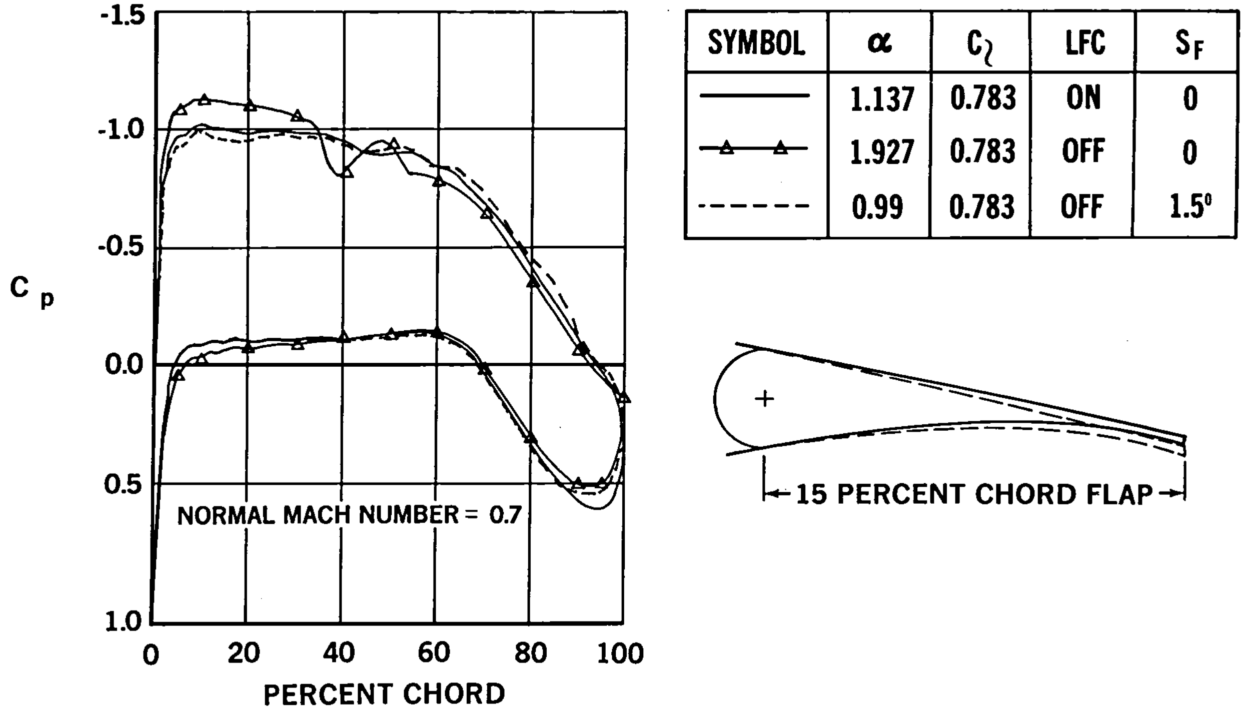


FIGURE 6-13. EFFECT OF TRAILING EDGE FLAP ON AIRFOIL PRESSURE DISTRIBUTIONS

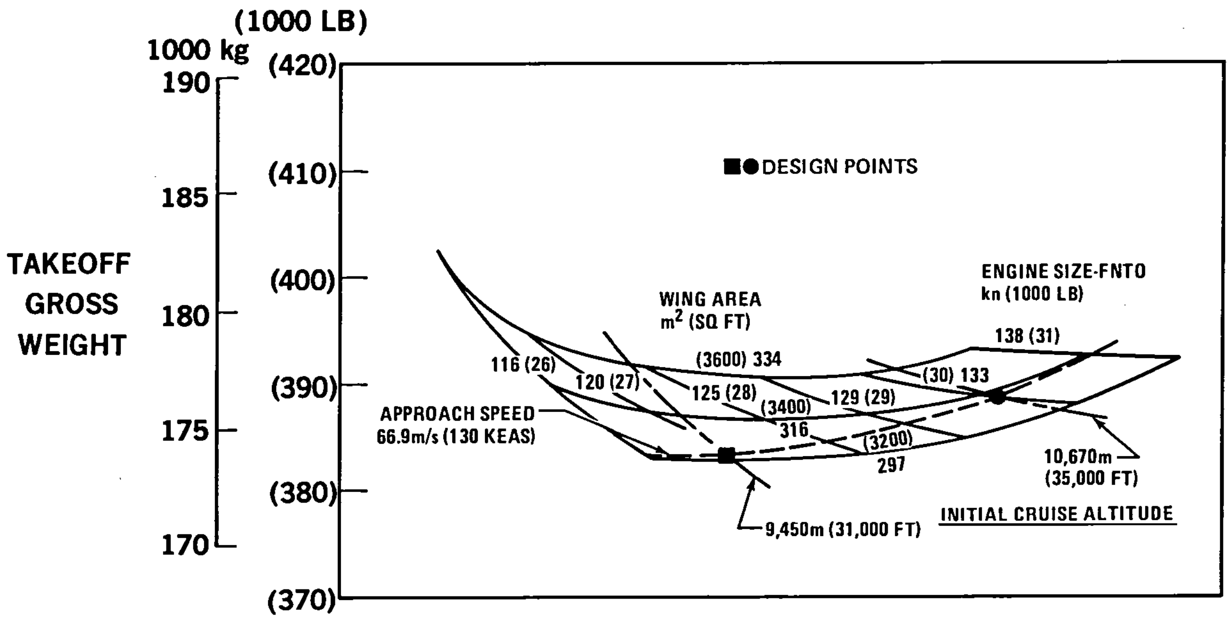


FIGURE 6-14. MISSION SIZING MATRIX FOR AR = 10, SUCTION ON BOTH SURFACES

Initial LFC Aircraft Configuration

The interior layout for a mixed-class configuration with amenities appropriate to the 9,260-km (5,000-n-mi) range is shown in Figure 6-15. The three-view and overall characteristics for the LFC aircraft are presented in Figure 6-16.

24 FIRST CLASS — 965- and 990-mm (38 AND 39 IN.) SEAT PITCH

275 ECONOMY — 864-mm (34 IN.) SEAT PITCH

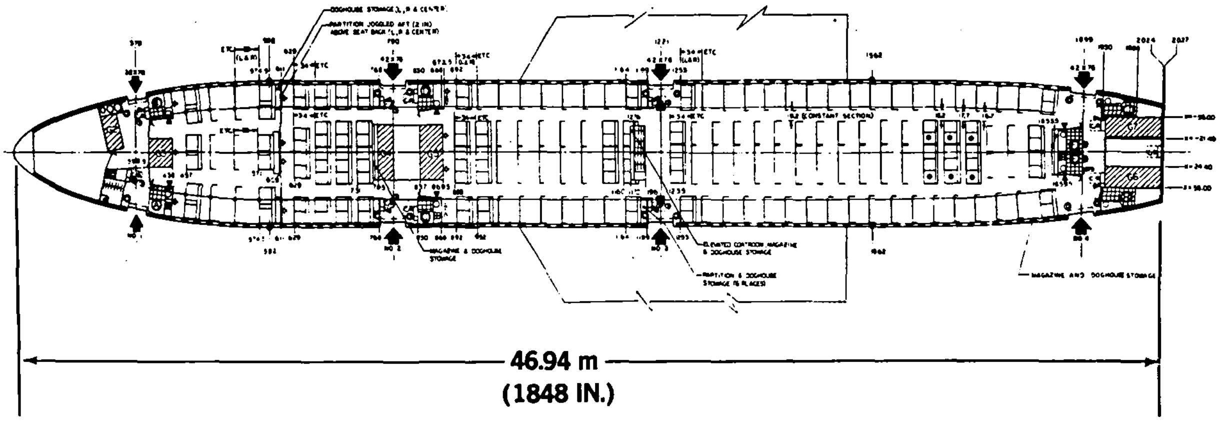


FIGURE 6-15. INTERIOR ARRANGEMENT, MIXED CLASS

	WING	HORIZ	VERT
AREA m^2 (FT^2)	331 (3560)	98.8 (1064)	62.0 (667)
ASPECT RATIO	10	5	1.1
TAPER RATIO	0.25	0.4	0.7
SWEEP	30 DEG	30 DEG	40 DEG
THICKNESS RATIO	0.117 AVG	0.11	0.11
TAIL VOLUME COEF	–	1.23	0.0646

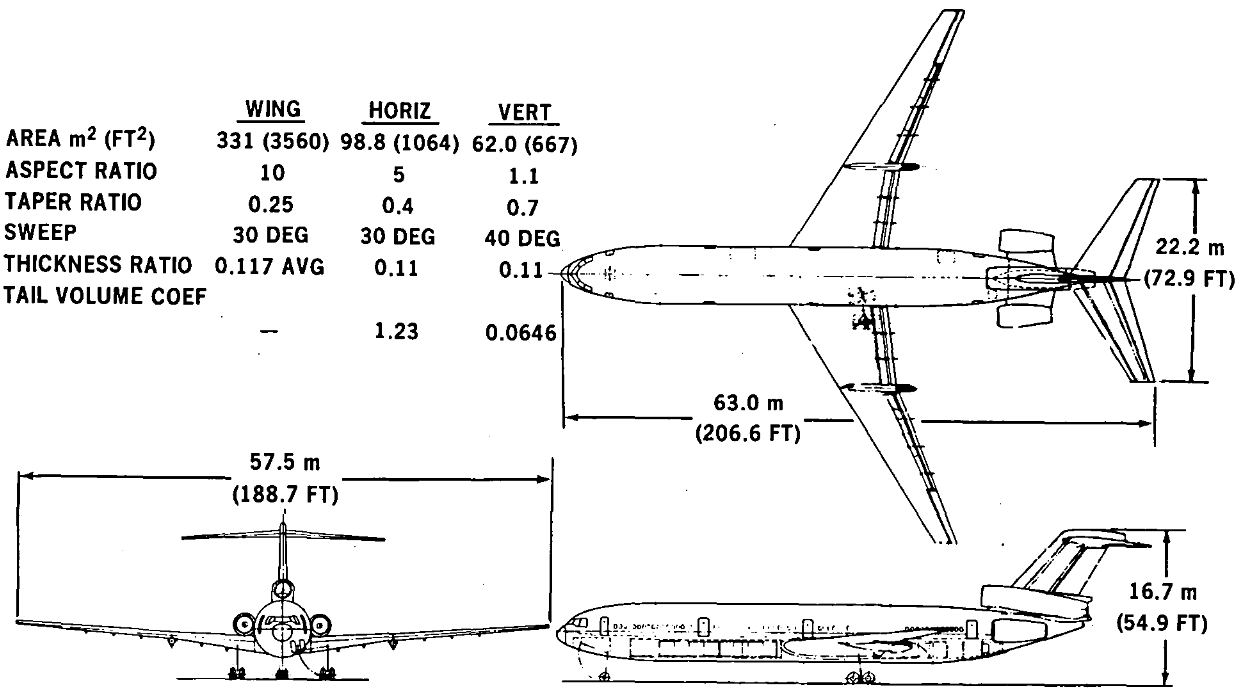


FIGURE 6-16. LFC AIRCRAFT UPPER AND LOWER AIRFOIL SURFACE LAMINARIZED TO 70-PERCENT CHORD

INITIAL COMPARISON WITH TURBULENT AIRCRAFT

For a meaningful evaluation of the LFC aircraft, comparison with an equivalent turbulent aircraft is necessary. A turbulent aircraft was designed for the same mission and benefited from the same level of advanced technology, except for LFC. The resulting configuration is shown in Figure 6-17.

	WING	HORIZ	VERT
AREA — m^2 (FT^2)	260 (2800)	89.6 (964)	47.2 (508)
ASPECT RATIO	10.85	3.95	1.60
TAPER RATIO	0.25	0.35	0.35
SWEEP	30 DEG	35 DEG	40 DEG
THICKNESS RATIO	0.127 AVG	10	10.5
TAIL VOLUME COEF	—	1.38	0.079

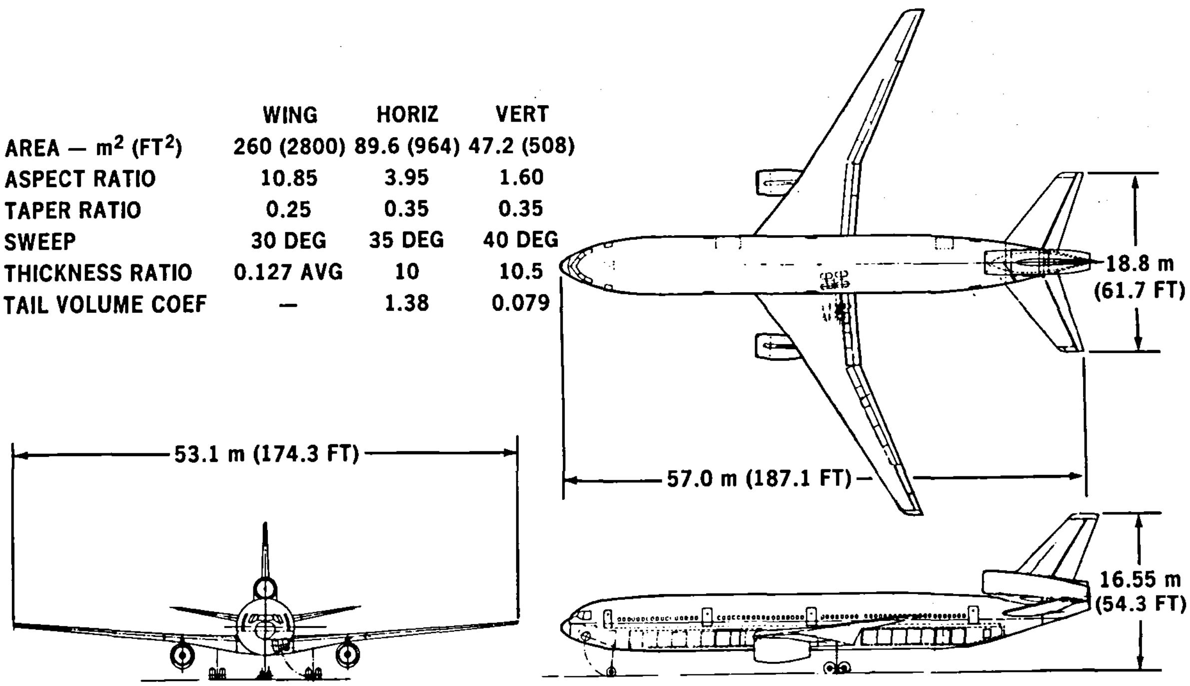


FIGURE 6-17. ADVANCED TURBULENT AIRCRAFT

Comparison of the initial LFC and turbulent configurations showed that the primary objective of fuel/energy saving was achieved. The LFC aircraft required 22-percent less fuel for the same mission.

The initial study and comparison also focused attention on a number of concerns regarding the initial LFC aircraft configuration.

- The contamination of the LFC wing surface due to impact with flying insects must be prevented. Protuberances on the surfaces greater than about 0.1 mm (0.004 in.) could initiate a turbulent wedge on the wing surface and a large number of insect deposits creating overlapping wedges could make LFC ineffective. Protection against insects could be provided by a sufficiently large flow of liquid over the leading edge region and this could be distributed through the porous surface in the leading edge region. However, for the most economical use of suction for LFC and to counteract instability along the attachment line, suction should also be applied at the leading edge. This conflict created a practical design problem.
- Wing systems are normally installed and serviced through access doors in the lower surface. With laminar flow on the lower surface, it would be difficult to provide access doors that could be routinely opened and closed and still provide the continuity of suction and accurate contour required for LFC.
- The lower-wing surface is particularly vulnerable to damage from foreign objects thrown up from the runway and could create maintenance problems for a more sensitive LFC surface.

- A comparison of configurations showed that the LFC aircraft required 27 percent more wing area than the turbulent aircraft. This was partly due to the relatively poor maximum-lift capability of the LFC wing resulting from the absence of a leading edge high-lift device.

These concerns resulted in the LFC aircraft improvement studies described in the following section.

7. LFC AIRCRAFT IMPROVEMENT

SIMPLIFICATION OF THE LFC SYSTEM

The LFC system can be greatly simplified if LFC is used only on the upper wing surface. A study showed that the profile drag coefficient reduction that can be achieved with LFC extended to 85-percent chord on the upper surface is close to that obtainable with suction on both upper and lower surfaces to 70-percent chord, as used on the initial baseline configuration. The profile drag coefficients are compared in Figure 7-1.

An example of the simplification possible is illustrated in Figure 7-2, which shows the reduction in manifold ducting and the avoidance of a second compressor stage that results from the elimination of LFC from the lower surface.

The initial cost and maintenance costs are reduced by this simplification. Normal-access doors can be provided in the lower surface for maintenance of LFC and wing systems, and the lower surface is no longer critically affected by foreign object damage.

INCREASED MAXIMUM LIFT

Due to manufacturing and rigging tolerances and deflections occurring in flight, it is impractical to control the gap between a retractable surface and the wing closely enough to permit LFC across the joint. It is therefore not feasible to use a high-lift device at the wing leading edge with LFC on both upper and lower wing surfaces. A major advantage of using LFC on the upper surface only is that this allows the use of a high-lift device that can be retracted into the lower surface. This is illustrated in Figure 7-3. Even though ex-

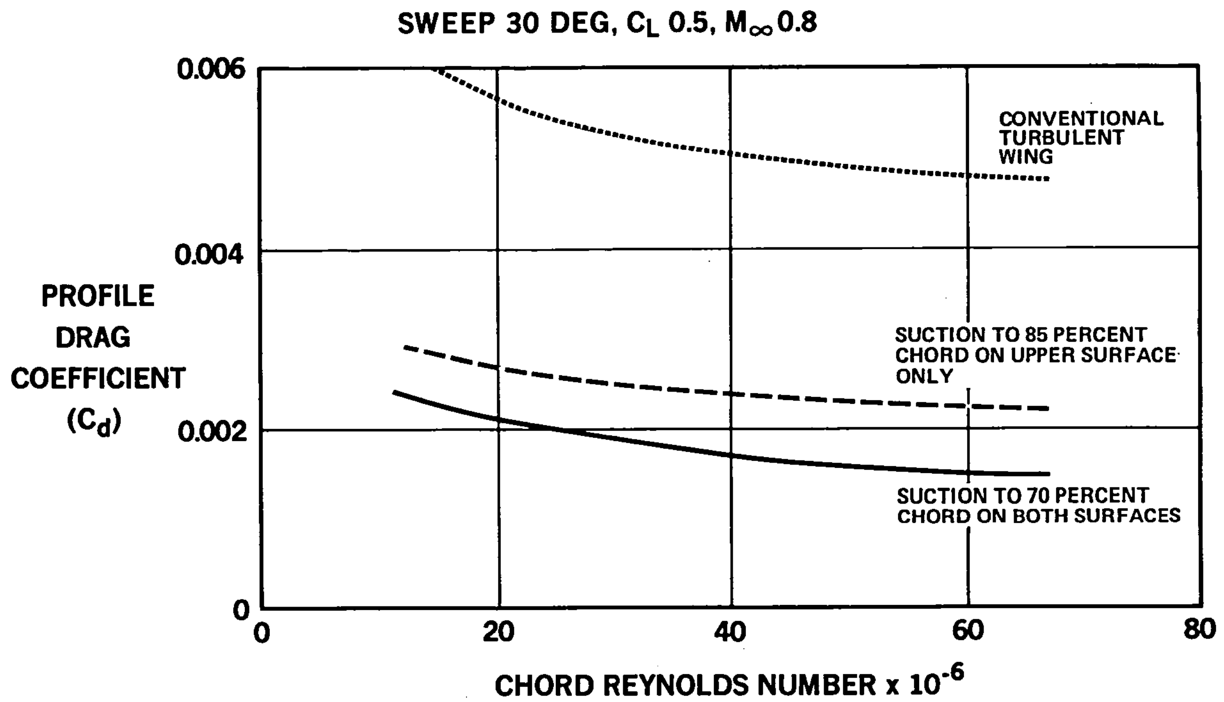
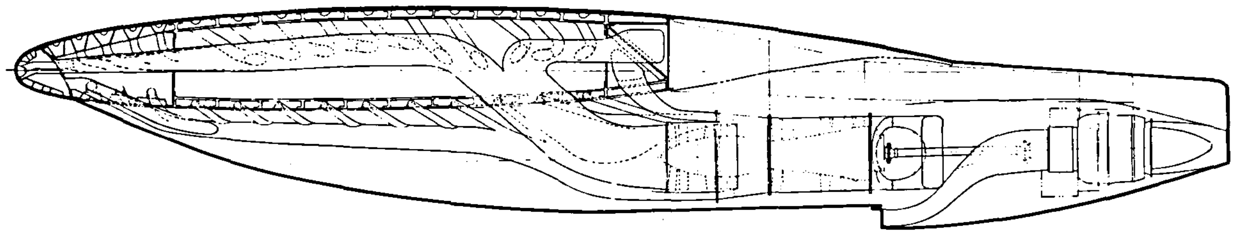
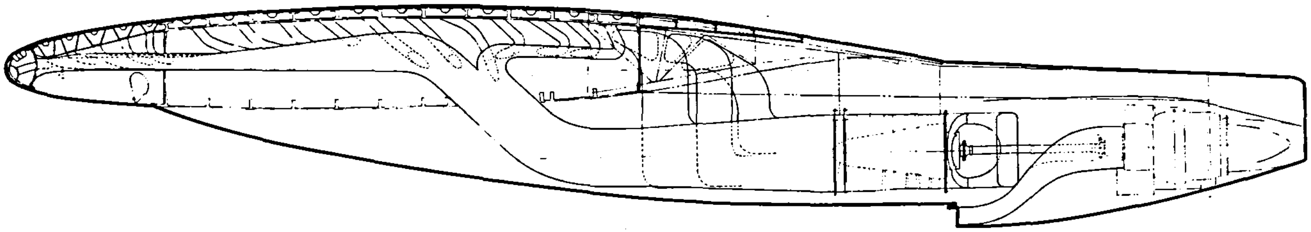


FIGURE 7-1. EFFECT OF LFC EXTENT ON PROFILE DRAG

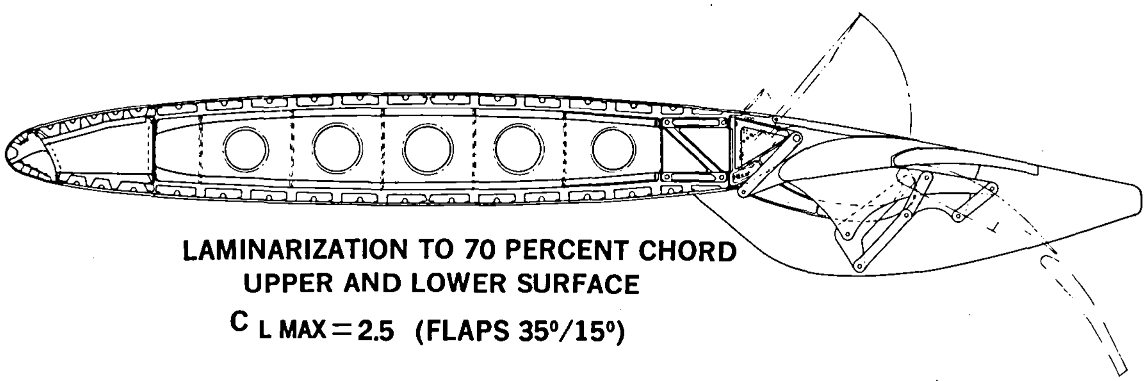


LAMINARIZATION TO 70 PERCENT CHORD
UPPER AND LOWER SURFACE

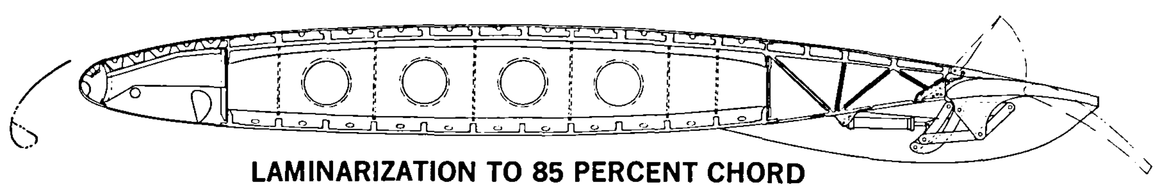


LAMINARIZATION TO 85 PERCENT CHORD
UPPER SURFACE ONLY

FIGURE 7-2. SUCTION SYSTEM MANIFOLDING INTEGRATION



LAMINARIZATION TO 70 PERCENT CHORD
UPPER AND LOWER SURFACE
$C_{L\,MAX} = 2.5$ (FLAPS 35°/15°)



LAMINARIZATION TO 85 PERCENT CHORD
UPPER SURFACE ONLY
$C_{L\,MAX} = 3.1$ (FLAP 30°)

FIGURE 7-3. COMPARISON OF LFC WING SECTIONS

tending LFC to 85-percent chord limits the trailing edge flap size, the use of a leading edge device results in a 24-percent increase in maximum lift.

CONTAMINATION AVOIDANCE

The leading edge device can also be designed to effectively shield the wing leading edge region against insect impingement. Its effectiveness was analyzed using an existing computer program normally used for wing icing analysis. The program takes into account the aerodynamic shape of the wing including the leading and trailing edge flap elements. The mass and drag coefficients for the icing particles were adjusted to represent the ballistic and drag characteristics of various insects. Typical computer printouts for −4 and +15-degree angles of attack with flaps extended are shown in Figures 7-4A and 7-4B respectively.

To support the analysis, insect impingement tests were run in the icing tunnel at NASA Lewis (see Figure 7-5). The model consisted of a DC-9 wing section incorporating porous surfaces in the leading edge region and a fixed shield. The insect injection tube assembly was set at an angle so that several streamlines would be represented across the span of the model.

The results showed that the shield could provide full protection against contamination from large flying insects that would have impacted close to the leading edge. A glancing impact further aft on the upper surface could occur at the most negative angles of attack with very large insects. At the maximum angle of attack it was possible for the smallest insects to be sufficiently deflected by the airflow to impact on the lower surface close to the leading edge. It is anticipated that the resulting contamination will be insufficient to cause loss of LFC but additional protection could be provided by spraying liquid onto the surface from nozzles attached to the shield, as shown in Figure 7-6. Flight testing is needed to determine whether this is necessary.

When any liquid is applied to a finely perforated surface there is a tendency for it to be retained within the perforations. LFC suction differential pressure across the surface is insufficient to clear the porosity and a purging system is therefore needed. A schematic diagram of a suction system with purging capability is shown in Figure 7-7. Experimental results of the time to clear the surface against differential pressure are plotted in Figure 7-8. The propylene glycol methyl ether (PGME) freezing-point depressant liquid selected for the spray system can be cleared within a few seconds at a low pressure differential of 2 kPa (0.3 psi).

ACA WING AT 80-PERCENT SPAN LOCATION

INSECT AERO COEF (K) 0.100 PER FOOT
ANGLE OF ATTACK −4.0 DEGREES

CHORD LENGTH=2.47 m (97.1 IN.)
AIRSPEED=74.6 m/s (145 KIAS)

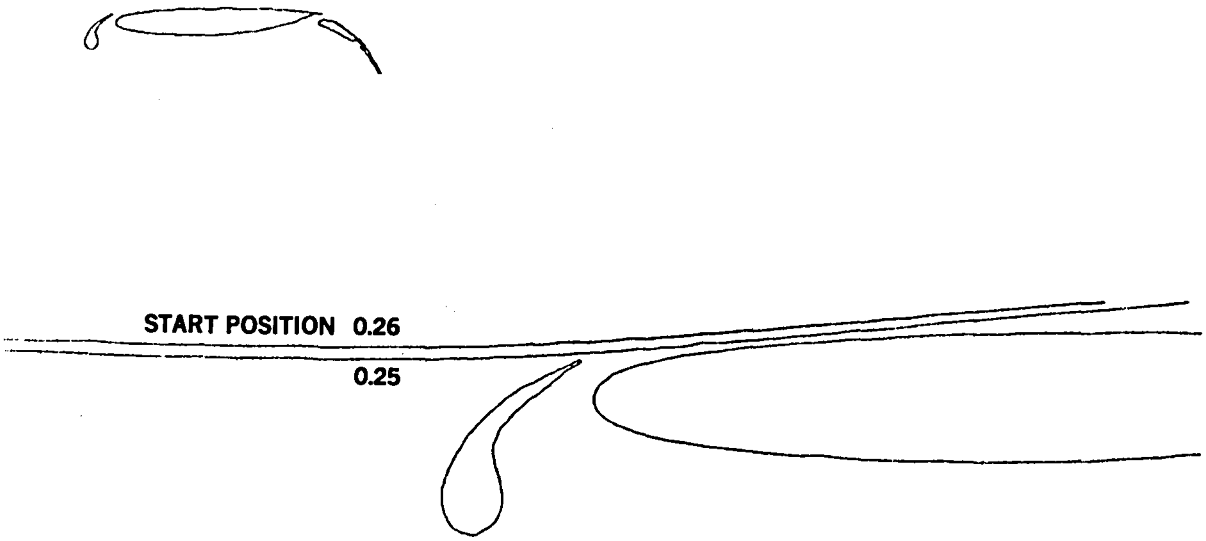


FIGURE 7-4A. INSECT TRAJECTORIES – SEA LEVEL TAKEOFF, –4-DEGREE ANGLE OF ATTACK

INSECT AERO COEF (K) 0.100 PER FOOT
ANGLE OF ATTACK 15.0 DEGREES

CHORD LENGTH 2.47 m (97.1 IN.)
AIRSPEED 74.6 m/s (145 KIAS)

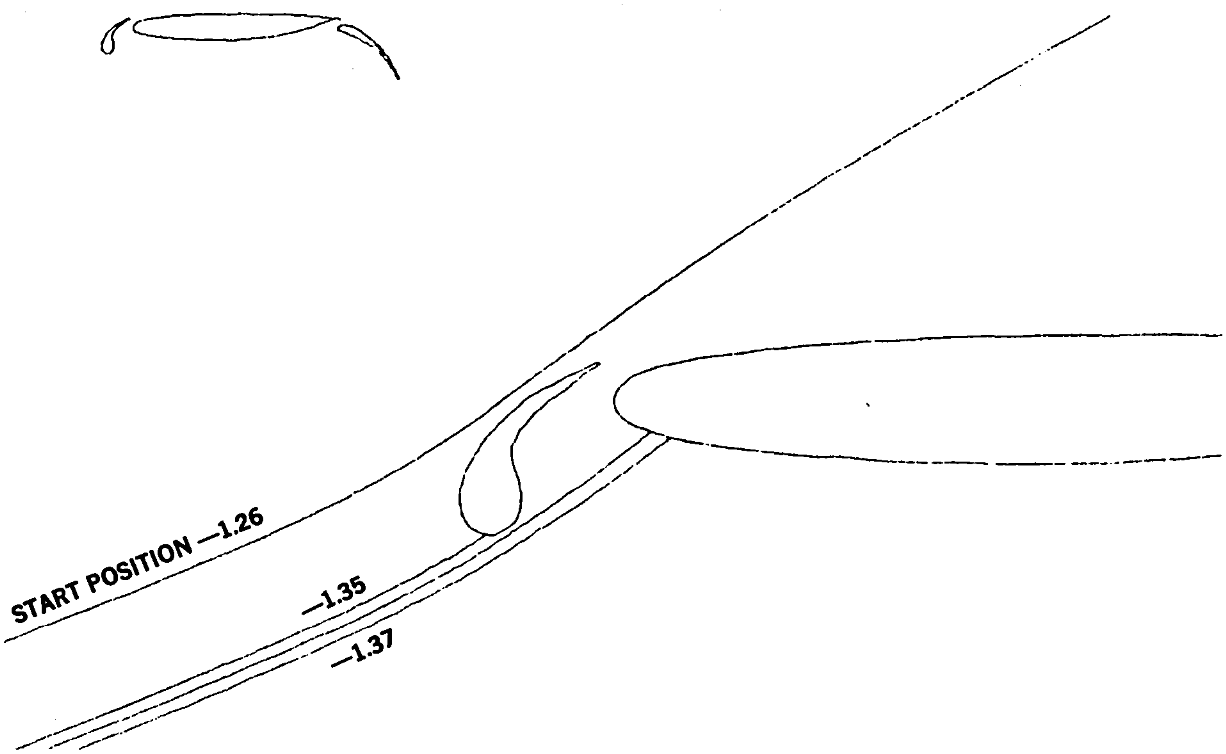


FIGURE 7-4B. INSECT TRAJECTORIES – SEA-LEVEL TAKEOFF, 15-DEGREE ANGLE OF ATTACK

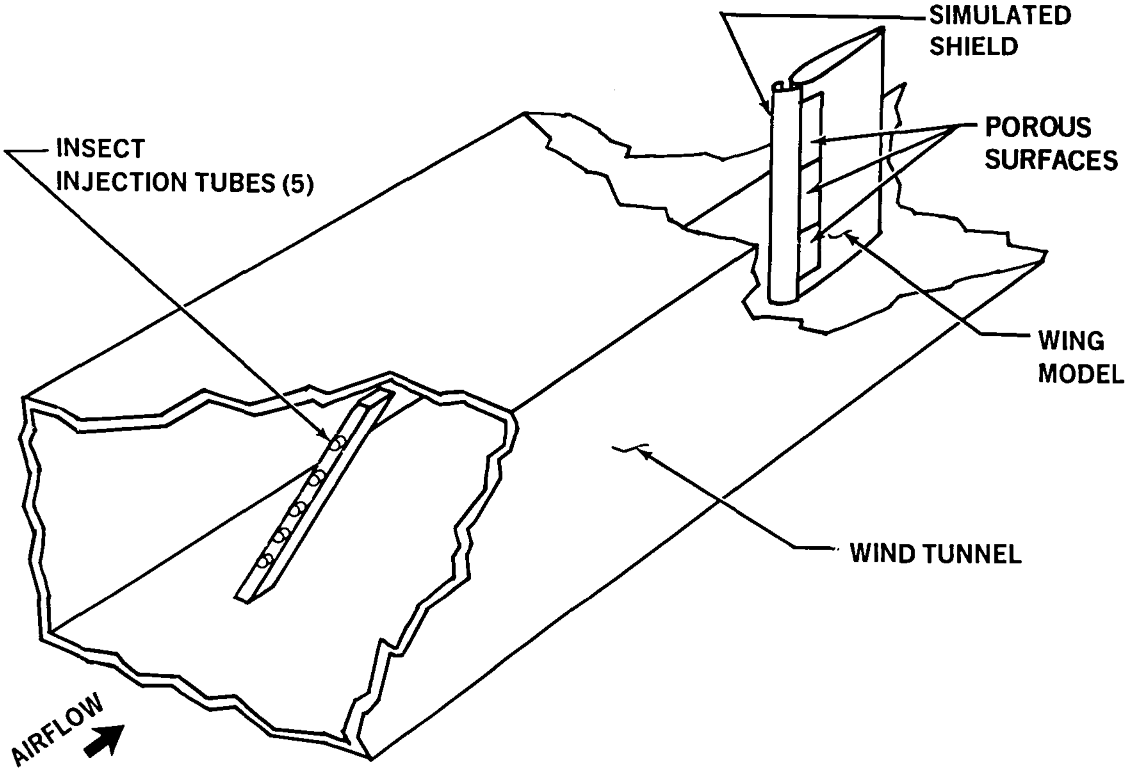


FIGURE 7-5. INSECT IMPINGEMENT TESTS IN LEWIS ICING TUNNEL

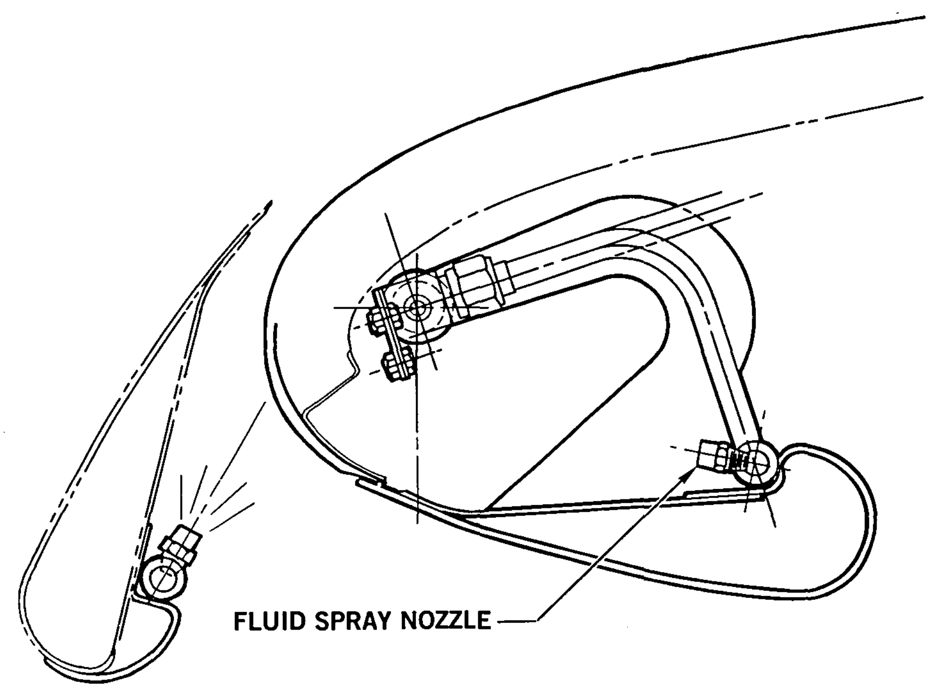


FIGURE 7-6. SPRAY CONCEPT

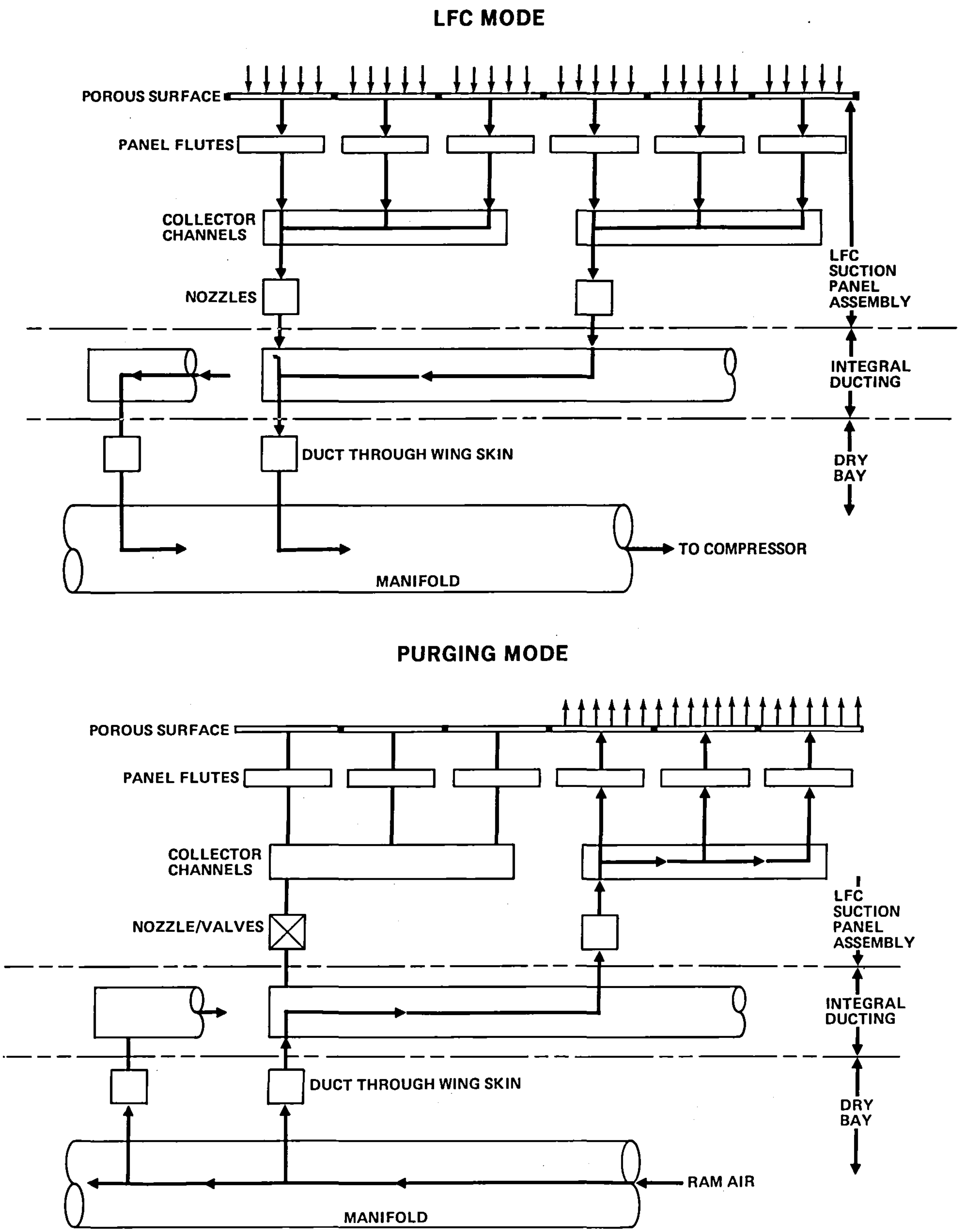


FIGURE 7-7. SCHEMATIC OF SUCTION SYSTEM

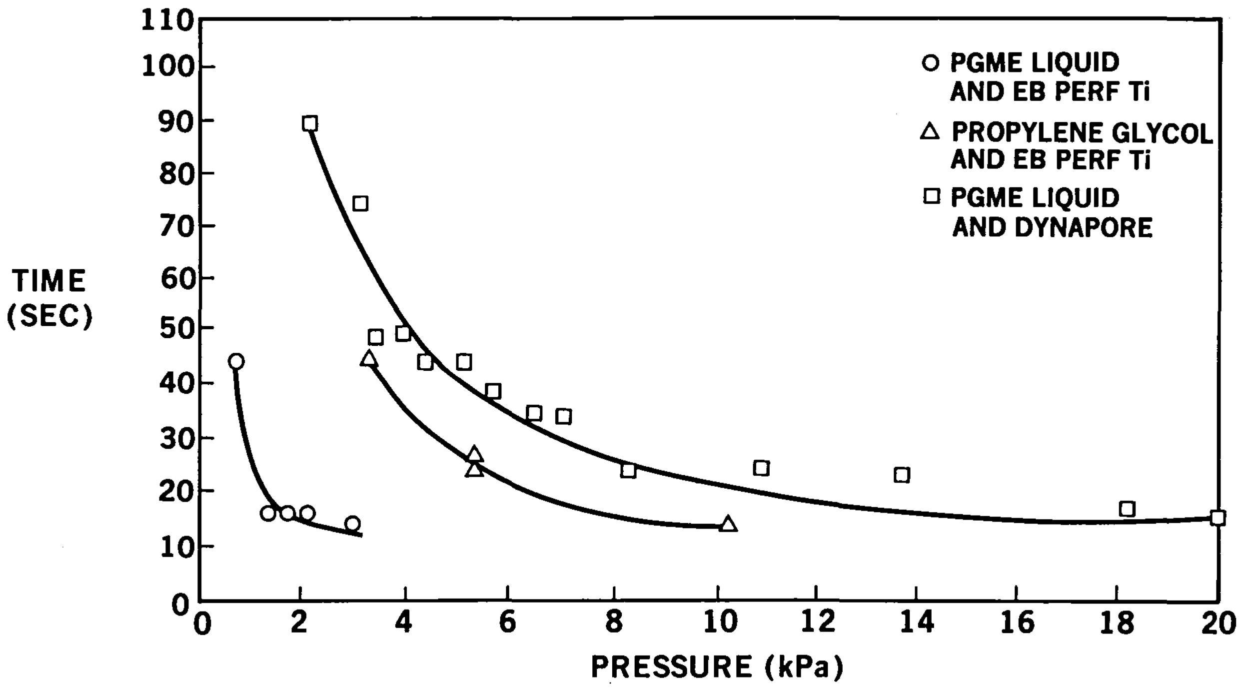


FIGURE 7-8. TIME TO CLEAR LIQUID FROM POROUS SURFACE

8. FINAL LFC AIRCRAFT CONFIGURATION

An aircraft was configured using LFC on the upper wing surface only (USO) to 85-percent chord, as illustrated in Figure 8-1. The absence of LFC on the lower surface allowed the use of a shield retracting into the lower wing surface to be deployed forward of the wing leading edge. This provided protection against contamination from flying insects and increased the maximum wing lift.

The LFC glove panel consisted of an electron beam-perforated suction surface bonded to a corrugated fiberglass panel. The suction airflow was collected initially in the panel flutes, then transferred to spanwise ducts formed by external stiffeners on the upper surface of the wing box. Manifold ducting was then used to transfer the air to suction pumps driven by gas turbine engines located at about 40-percent semispan.

The main wing box was of carbon-fiber/epoxy construction and the wing was designed to meet strength, flutter, and stiffness requirements. The aircraft was sized to meet the mission requirements (Section 6). A three-view of the resulting configuration is shown in Figure 8-2.

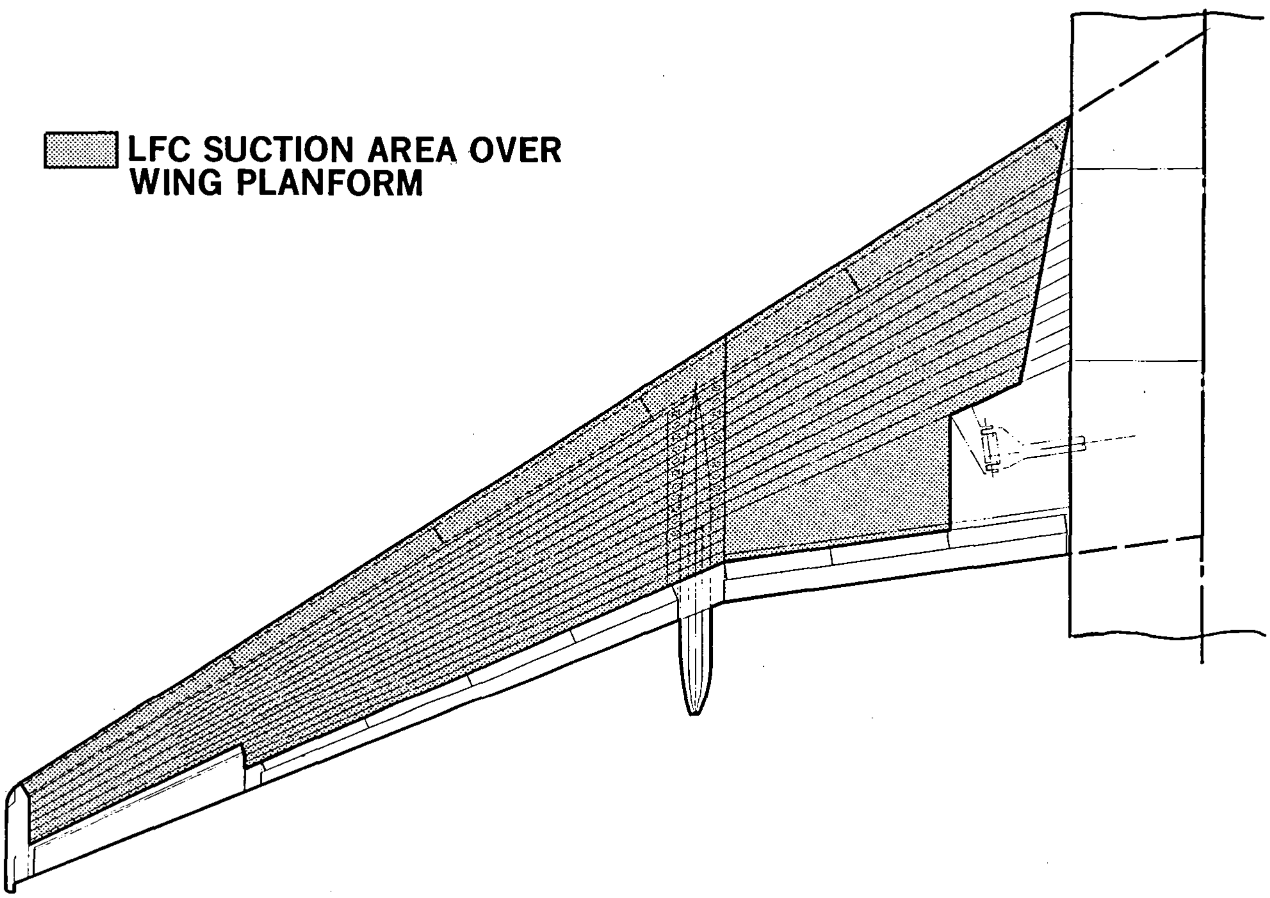
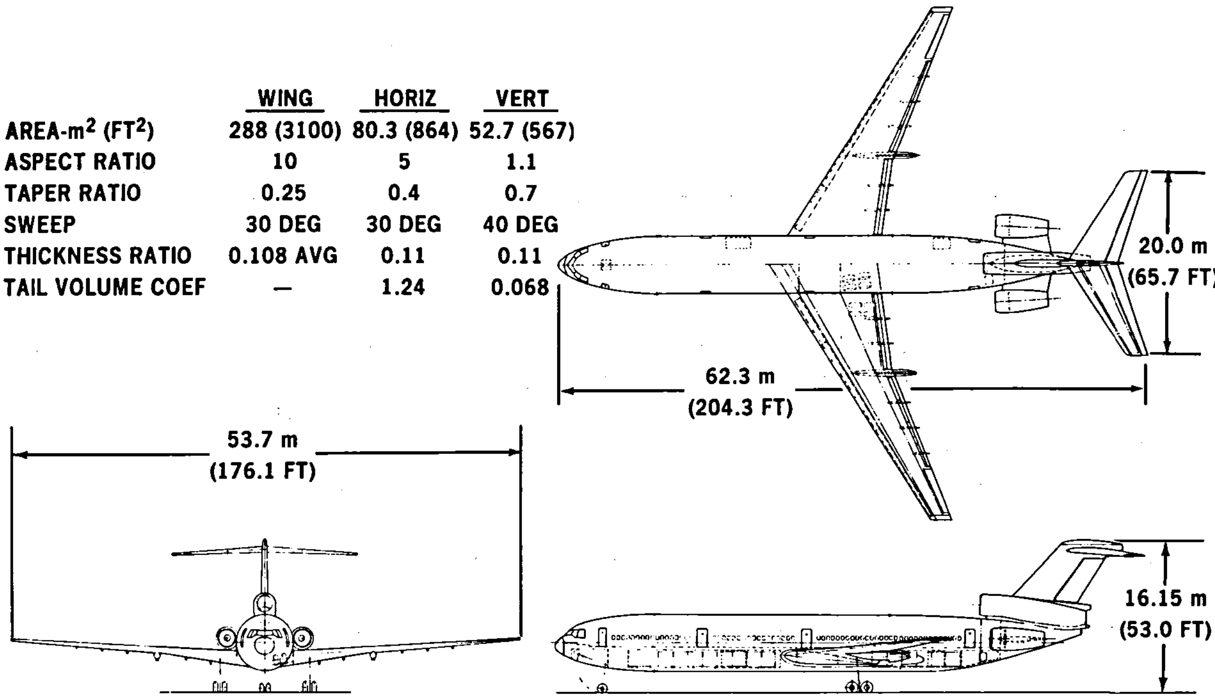


FIGURE 8-1. LFC AREA – UPPER SURFACE SUCTION ONLY



	WING	HORIZ	VERT
AREA-m^2 (FT^2)	288 (3100)	80.3 (864)	52.7 (567)
ASPECT RATIO	10	5	1.1
TAPER RATIO	0.25	0.4	0.7
SWEEP	30 DEG	30 DEG	40 DEG
THICKNESS RATIO	0.108 AVG	0.11	0.11
TAIL VOLUME COEF	—	1.24	0.068

FIGURE 8-2. LFC AIRCRAFT – WING UPPER AIRFOIL SURFACE ONLY LAMINARIZED TO 85-PERCENT CHORD

PERFORMANCE COMPARISON

Table 8-1 compares the characteristics of the USO aircraft with an updated version of the previous LFC configuration with suction to 70 percent chord on both upper and lower wing surfaces. As expected, the USO aircraft required significantly less wing area, and in addition all of the significant cost and performance parameters were improved. The percentage improvements are listed in Table 8-2. The practical design objectives of reduced vulnerability to both insect contamination and foreign object damage, and the provision of normal wing access through doors in the lower surface, were also achieved.

A comparison of aircraft characteristics for the advanced turbulent aircraft and the selected LFC aircraft is presented in Table 8-3. The empty weight of the LFC aircraft is higher but the takeoff weight is less due to a reduction in required fuel. The approach speed and field length for the LFC aircraft are both less than the respective 67 m/s (130 kn) and 3,048 m (10,000 ft) requirements.

ECONOMICS

A study was made of comparative economics to complete the comparison of alternative LFC and turbulent aircraft configurations. The following ground rules were used for the study:

- ROM costing level of estimating
- 1976 dollars used throughout

TABLE 8-1

LFC AIRCRAFT CHARACTERISTICS COMPARISON

		UPPER AND LOWER-SURFACE LFC TO 70-PERCENT CHORD		UPPER-SURFACE LFC TO 85-PERCENT CHORD	
POWER PLANT		3 ADVANCED	TURBOFANS	3 ADVANCED	TURBOFANS
SLS THRUST/ENGINE	kN (LB)	145.4	(32,690)	139.8	(31,430)
WING					
AREA	m^2 (FT^2)	331	(3,560)	288	(3,100)
SWEEPBACK, c/4	DEG	30		30	
AR		10		10	
TAPER RATIO		0.25		0.25	
AIRFOIL t/c_{AVG}		11.7		10.3	
WEIGHT					
TOGW	kg (LB)	188,663	(415,930)	183,396	(404,320)
OEW	kg (LB)	97,899	(215,830)	93,690	(206,550)
FUEL BURNED	kg (LB)	49,745	(109,670)	49,260	(108,600)
FUEL RESERVES	kg (LB)	9,709	(21,405)	9,147	(20,165)
CRUISE C_L		0.5		0.56	
L/D		23.1		22.2	
$V_{APPROACH}$	m/s (KN)	66.9	(130)	64	(124.5)
TAKEOFF FIELD LENGTH	m (FT)	2,632	(8,635)	2,615	(8,580)

TABLE 8-2

COMPARISON OF SIGNIFICANT PERFORMANCE AND COST PARAMETERS FOR ALTERNATIVE LFC AIRCRAFT

		LFC ON BOTH WING SURFACES TO 70-PERCENT CHORD		LFC ON UPPER SURFACE ONLY TO 85-PERCENT CHORD		CHANGE (%)
WING AREA	m^2 (FT^2)	331	(3,560)	288	(3,100)	−13.0
WEIGHT (OEW)	kg (LB)	97,900	(215,830)	83,690	(206,550)	−4.3
SLS THRUST/ENGINE	kN (LB)	145.4	(32,690)	139.8	(31,430)	−3.9
FUEL BURNED	kg (LB)	49,745	(109,670)	49,260	(108,600)	−1.0
INITIAL COST ($ MILLION)		48.39		46.52		−3.9

TABLE 8-3
AIRCRAFT CHARACTERISTICS COMPARISON

5,000-N-MI RANGE 69,000-POUND PAYLOAD

		TURBULENT		UPPER-SURFACE LFC TO 85-PERCENT CHORD	
POWER PLANT		3 ADVANCED TURBOFANS		3 ADVANCED TURBOFANS	
SLS THRUST/ENGINE	kN/(LB)	147.9	(33,240)	139.8	(31,430)
WING					
AREA	m^2 (FT^2)	260	(2,800)	288	(3,100)
SWEEPBACK, c/4	DEG	30		30	
AR		10.85		10	
TAPER RATIO		0.25		0.25	
AIRFOIL t/c_{AVG}		12.7		10.3	
WEIGHT					
TOGW	kg (LB)	191,854	(422,965)	183,396	(404,320)
OEW	kg (LB)	91,401	(201,505)	93,690	(206,550)
FUEL BURNED	kg (LB)	60,217	132,755	49,260	(108,600)
FUEL RESERVES	kg (LB)	8,936	(19,700)	9,147	(20,165)
CRUISE C_L		0.58		0.56	
L/D		17.5		22.2	
$V_{APPROACH}$	m/s (KN)	63.5	(123.5)	64	(124.5)
TAKEOFF FIELD LENGTH	m (FT)	3,048	(10,000)	2,615	(8,580)

- 14-year aircraft life
- 5,000 hour-per-year utilization
- 400 aircraft production/single manufacturer
- 45-cents-per-gallon fuel
- Modified 1967 ATA DOC equations used
- Cost of landing fees and cabin attendants included
- Factors and coefficients based on Douglas experience with operators.

The results, presented in Table 8-4, include those for both the three-engined and four-engined configurations considered during the study. The selected three-engined configurations had lower initial and operating costs for both LFC and turbulent aircraft configurations than the equivalent four-engined configurations.

TABLE 8-4

COST SUMMARY

	STUDY I		STUDY II			STUDY IV	
	TURB-4	LFC-B4	LFC-B3	LFC-B4	TURB-3	LFC-B3	LFC-U3
AIRPLANE COST							
FLYAWAY PRICE ($M)	46.35	49.10	52.62	53.99	45.57	48.39	46.52
WITHOUT ENGINES ($M)	—	—	—	—	39.7	42.6	40.9
DIRECT OPERATING COST*							
$/AIRCRAFT km	3.44	3.41	3.44	3.57	3.43	3.41	3.34
($/AIRCRAFT N MI)	(6.38)	(6.31)	(6.37)	(6.62)	(6.35)	(6.32)	(6.19)
¢/SEAT km	1.152	1.140	1.151	1.195	1.147	1.141	1.118
(¢/SEAT N MI)	(2.134)	(2.110)	(2.131)	(2.213)	(2.125)	(2.113)	(2.072)

TURB-3 = TURBULENT AIRCRAFT — 3 ENGINES
TURB-4 = TURBULENT AIRCRAFT — 4 ENGINES

LFC-B3 = LFC BOTH WING SURFACES — 3 ENGINES
LFC-B4 = LFC BOTH WING SURFACES — 4 ENGINES
LFC-U3 = LFC UPPER SURFACE ONLY — 3 ENGINES

*ASSUMING 12¢/LITER (45¢/GALLON) FUEL COST

Although a fuel cost of only $0.12 per liter ($0.45 per U.S. gallon) was a ground rule for this study, the effects of increases in fuel costs up to $0.6 per liter ($2.3 per gallon) were considered. The effects on DOC are shown in Figure 8-3. The economic benefit resulting from LFC increases rapidly with rising fuel costs and the DOC for the selected LFC aircraft could be expected to be about 9 percent less than for an equivalent advanced turbulent aircraft by the time an LFC aircraft could become operational.

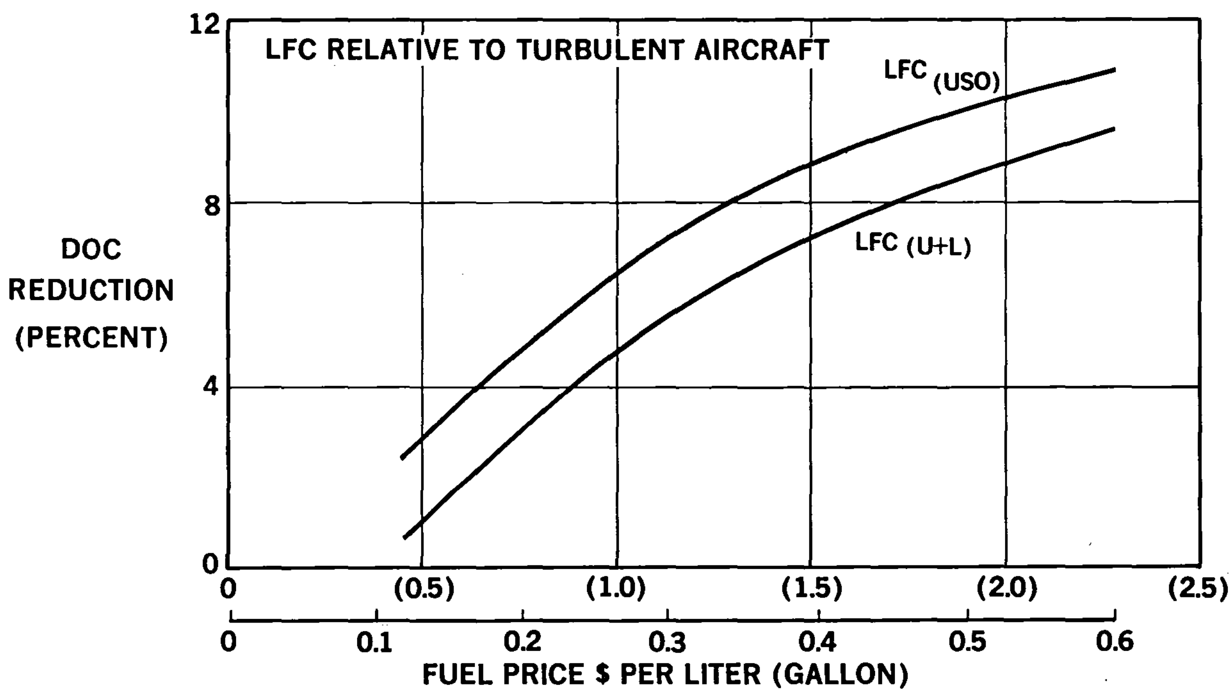


FIGURE 8-3. REDUCTION IN DOC AS A FUNCTION OF FUEL COST

9. CONCLUSIONS AND RECOMMENDATIONS

LFC SURFACE

Results of tests conducted on a wide variety of possible LFC suction surfaces indicate that electron beam (EB) perforated titanium has the greatest potential for achieving LFC under practical aircraft operating conditions. It provides a tough, corrosion-resistant, effectively smooth LFC surface that can be worked satisfactorily to strain levels corresponding to those of an advanced-technology wing structure.

Low-speed wind tunnel testing showed that the 0.0635-mm (0.0025-in.) diameter perforations through the surface are sufficiently small so they will not cause transition or attract particles onto the surface that would trip the flow. On the other hand, the perforations are large enough to allow purging in flight of any trapped liquids and to allow cleaning to be accomplished satisfactorily using simple steam-cleaning equipment without removing the LFC panel.

LFC panels with woven stainless steel Dynapore surfaces were also thoroughly investigated. Their LFC characteristics were very good but structural and damage-resistance properties were inferior to those of the EB-perforated titanium.

In support of porous surfaces in general, there were indications that due to inherent noise-damping characteristics, they would be less sensitive to the effects of noise interference. It is also anticipated that any shock waves at the surface would have less adverse effects.

LFC AIRCRAFT CONFIGURATION

The final LFC aircraft configuration proposed by Douglas (Figure 8-2) utilizes suction to 85-percent chord on the wing upper surface only. This has been shown to be more than competitive with a configuration having suction on both upper and lower wing surfaces to 70-percent chord (Figure 6-16). By comparison, the configuration with LFC on the upper wing surface only had lower weights, lower initial cost, lower operating cost, and lower fuel consumption for the same mission. Some other advantages are listed here.

- Simplification of the LFC system.
- Vulnerability of the lower LFC surface to damage from foreign objects thrown up from the runway is avoided.
- The possibility of fuel leakage into the LFC panels and integral ducts is reduced.
- Conventional access panels to wing leading and trailing edge systems and fuel tanks can be provided for inspection and maintenance without affecting any LFC surface.
- Maintenance costs are reduced.
- A shield for contamination avoidance can be deployed forward of the wing leading edge and be retracted into the lower surface when not required.

- The shield can be designed geometrically to function as a high-lift device.
- The use of a retractable high-lift device allows the safe use of a sharper leading edge on the basic wing. This results in a reduction — or possible elimination — of suction requirements along the attachment line.

COMPARISON WITH ADVANCED TURBULENT AIRCRAFT

The study indicates that the proposed LFC configuration should result in a practical LFC transport aircraft providing fuel savings of at least 18 percent compared with those of the equivalent advanced turbulent aircraft shown in Figure 6-17. With LFC, although the manufactured empty weight is higher by 2,300 kg (5,000 lb), the takeoff gross weight is lower by 8,500 kg (18,600 lb) and the direct operating cost would be reduced by more than 8 percent.

RECOMMENDATIONS

Considerable progress has been made under this contract in the evaluation of laminar flow control system concepts for subsonic commercial transport aircraft and the use of porous suction surfaces has been demonstrated as a practical approach to achieving LFC. The configuration selected was shown as having very large fuel saving potential and to be economically advantageous compared with an equally advanced turbulent configuration. With a shielded leading edge and LFC on the upper wing panels only, the LFC surface is well protected from environmental contamination and damage. Normal access for inspection and maintenance is provided through the lower wing surface. The progress achieved justifies a continuation of the design, development, and testing that will be necessary before an LFC system is ready for application to production commercial transport aircraft.

The follow-on programs already sponsored by NASA — Contract NAS1-16234 on LFC structural surface development and testing, and Contract NAS1-16220 on flight-testing a JetStar aircraft LFC leading edge system — are logical and necessary steps toward the practical application of LFC to transport aircraft. The NASA LFC high-speed wind tunnel program at Langley, for which Douglas is supplying perforated LFC glove panels for the upper surface of a swept-wing model under Contract NAS1-16892, will test performance at high Mach numbers. Low-speed wind tunnel testing at Douglas has already demonstrated that porous and perforated surfaces can be used to satisfactorily achieve LFC on a 30-degree swept wing at Reynolds numbers per unit length approaching those of high-altitude cruising conditions.

The structural program is needed to develop further an efficient LFC suction panel that is compatible with strain levels in the primary wing structure. It should include design and testing of *small* test specimens and panels *large* enough to check Euler buckling between fasteners attaching the panel to the primary structure. Assuming that a composite wing is to be developed under a separate structural development program, an overall LFC wing structure design program is unnecessary. Panel joints also require further development. They must be designed to minimize local blockage of porosity and to retain a sufficiently smooth and wave-free surface during cruising flight. Both design work and testing are necessary.

The JetStar flight test should demonstrate the feasibility of achieving LFC under realistic operating conditions. The leading edge test specimen will be subjected to the environmental effects of rain, ice, and insect impingement. The LFC system will also be tested on a swept wing with regions of cross-flow and possible attachment line instabilities.

Full-Chord LFC Glove

Following the JetStar flight tests, it will be necessary to flight-test a full-chord glove to test LFC back to 85-percent chord where the effects of cross-flow and an adverse pressure gradient are combined. It is suggested that this testing should be done on a larger aircraft such as a DC-9 which offers the advantages of a clean wing and aft-located engines. A study of full-chord LFC glove configurations has shown that the DC-9 would be practical for this purpose. Figure 9-1 shows how the LFC glove could be superimposed on the existing DC-9 wing box structure. To obtain the maximum benefit from a full-chord glove flight test, Douglas proposed and presented the configuration shown in Figure 9-2 following a design study completed during 1979. The splitting of the suction surfaces into separate regions, one on each side, offers two advantages. First, the size of the suction ducting that must be accommodated within the glove envelope is halved and, second, the inboard region with its own peculiar LFC problems can be investigated separately.

The glove region outboard of the inboard LFC panel could be used to compare natural laminar flow, and the region inboard of the midspan LFC suction surface could be used to investigate the use of discrete suction applied only in the leading edge region. With the attachment line and cross-flow problems caused by sweep controlled by suction, extensive regions of laminar flow may be possible further aft, where the Tollmein-Schlichting instabilities can be controlled by the pressure gradients induced by the airfoil shape. This opens up the possibility of modifying the wings of existing aircraft to achieve significant LFC benefits at relatively low cost.

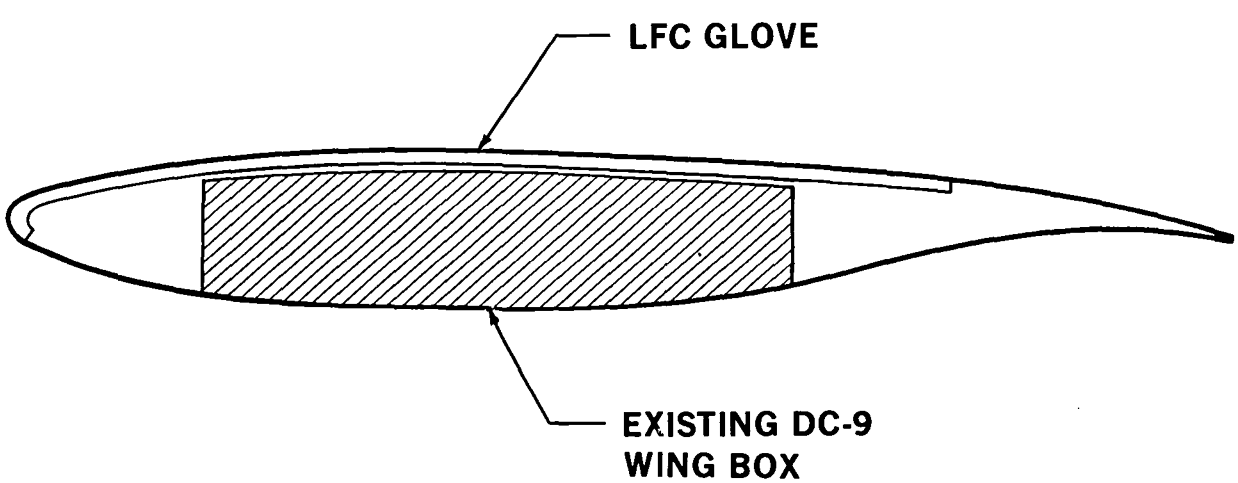


FIGURE 9-1. PROPOSED LFC GLOVE ON DC-9 WING BOX

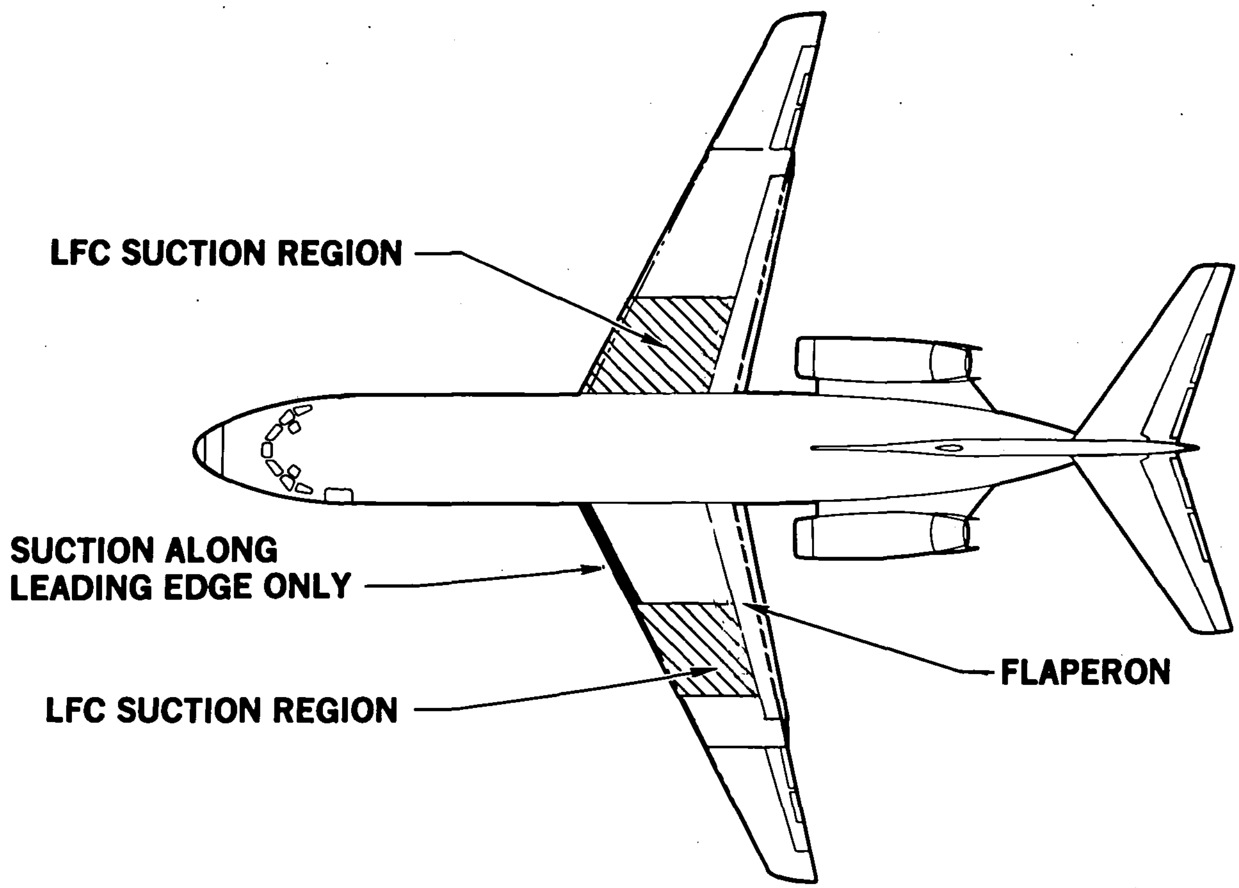


FIGURE 9-2. LFC WING GLOVE ON DC-9

Supporting LFC Programs

Before proceeding with the next phase of LFC development, a complete aerodynamic LFC wing design study is advisable. This should consider wing-sweep effects including the possibility of forward sweep. This is particularly advantageous with LFC because it results in reduced sweep at the leading edge for the same effective wing sweep.

Other items that need investigation include:

- Flow checks and pressure-drop measurements on simulated suction ducting and glove panels.
- Further development of perforating, welding, cutting, and forming techniques for perforated titanium sheet material.
- Further development and testing of environmental protection systems to either improve the liquid-dispensing system or preferably to eliminate it altogether.
- Further investigation and development of the possible use of a superplastic-formed diffusion-bonded all-titanium porous glove panel.
- Recycling of the base case LFC aircraft configuration to update the design and determine the cumulative effect of recent design improvements.

LFC Demonstration Aircraft

With the selected LFC design, it will finally be necessary to demonstrate the practical achievement of LFC over the complete wing of a sufficiently representative commercial transport aircraft. Otherwise, airlines and aircraft manufacturers would be unwilling to risk the level of expenditure necessary to launch an LFC aircraft program. An in-depth study at Douglas, funded by NASA, showed that the DC-9 would be suitable for this purpose. The configuration is shown in Figure 9-3. It would only require the addition of the LFC system and the installation of an LFC wing outboard of the center section. The existing center wing including the main gear could be retained. As a further cost saving, the same aircraft used for the glove testing could be modified to incorporate the complete LFC wing.

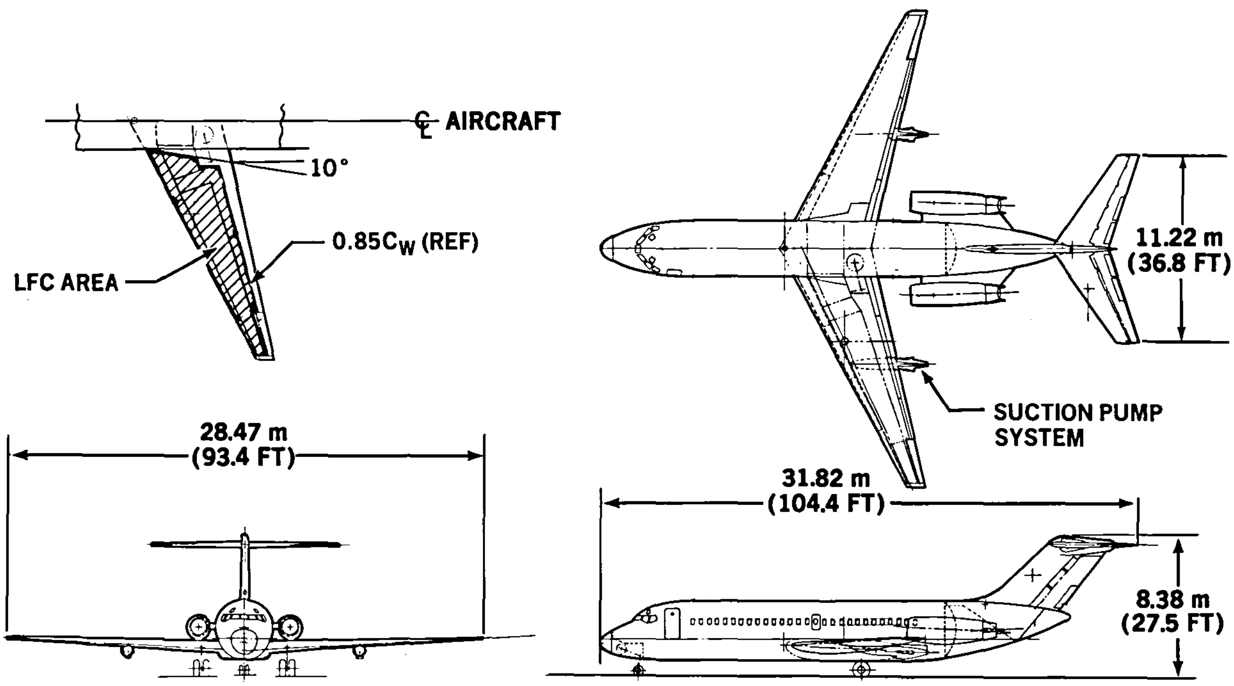


FIGURE 9-3. DC-9 WITH LFC WING

10. REFERENCES

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3. Ecklund, R. C., and Williams, N. R., Laminar Flow Control SPF/DB Feasibility Demonstration, NASA Contractor Report 165818, October 1981.

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16. Abstract
An evaluation was made of laminar flow control (LFC) system concepts for subsonic commercial transport aircraft. Configuration design studies, performance analyses, fabrication development, structural testing, wind tunnel testing, and contamination-avoidance techniques were included. As a result of trade studies, a configuration with LFC on the upper wing surface only, utilizing an electron beam-perforated suction surface, and employing a retractable high-lift shield for contamination avoidance, was selected as the most practical LFC system. The LFC aircraft was then compared with an advanced turbulent aircraft designed for the same mission. This comparison indicated significant fuel savings and reduced direct operating cost benefits would result from using LFC.

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